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APPLICATIONS OF SMALL ACCELERATORS

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APPLICATIONS OF SMALL ACCELERATORS

Proceedings of a Symposium
Sponsored by
The New York Metropolitan Section
of the
American Nuclear Society
New York, N.Y.
(April 8 and 9, 1969)

May 1970

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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
Rockville, Maryland 20852

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PREFACE

The Proceedings of the Symposium on Applications of Small Accelerators does not include all papers presented at the meeting. Several authors who spoke from notes expressed difficulty in developing these notes into final text and indicated they would discuss their papers with interested persons who contacted them directly. Accordingly, the full names, addresses, and telephone numbers of these authors are included in the text at the appropriate location.

Some 150-200 persons attended the sessions at various times, including students in nuclear engineering or radiation technology; in addition, after each paper was presented, open discussion was held during which additional comments were obtained. These discussions are not included in the proceedings.

The symposium was developed through a hard working committee consisting of:

James J. Barker, *C. W. Post College*
Marshall R. Cleland, *Radiation Dynamics Corporation*
Jerome L. Duggan, *University of Georgia*
Marvin Felder, *Picker-Nuclear Corporation*
John S. Laughlin, *Sloan-Kettering Institute*
Philip M. Lorio, *Columbia University*
James McLaughlin, *U.S. Atomic Energy Commission*
W. Herbert Pennington, *U.S. Atomic Energy Commission*
Adnan Waly, *Consultant*
Saul J. Harris, *U.S. Department of Health, Education, and Welfare -- Chairman.*

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ABSTRACT

The Symposium on Applicators of Small Accelerators was intended to provide present and prospective users of small accelerators with a concise review of current and future applications of such machines.

Small accelerators are considered to be those generally with operating potentials of up to 500,000 volts, as well as a few with higher potentials for special uses. The trend toward higher current machines was emphasized.

The following topics were discussed: The use of small accelerators in teaching; a nuclear physics teaching course with a 500-keV Van de Graaff; the use of the small accelerator in university laboratories; nuclear physics research; trends in medical application of small accelerators; the importance of the low energy accelerator in the small undergraduate physics department; fast neutron physics and thermonuclear research; trends in medical application of small accelerators; machine problems in generating neutrons for tumor therapy; operation of a medical cyclotron for the production of radioactive isotopes; the LINAC in radiology; industrial application of 14-MeV neutron generators; activation analysis in the electronics industry; ion implantation with accelerators; the radiation shielding problem; practical radiation protection measurements; a solution to tritium pump contamination for small accelerators; neutron radiography utilizing a small accelerator; and use of computers at accelerators.

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Armin W. Manning

Fast Neutron Physics and Thermonuclear Research
Chien Ho and *Michael Stamatelatos*

THE USE OF SMALL ACCELERATORS IN TEACHING*

by

Jerome L. Duggan**

Department of Physics

University of Georgia

Athens, Georgia

Introduction

In a conference similar to this one which was held in Oak Ridge (Ref. 1) in April of 1968, Dr. T. J. Prud'homme of Texas Nuclear Corporation showed a curve that illustrated the new accelerator installation trends. In the figure was plotted new installations as a function of time from 1963 through the middle of 1967. The installations were further divided into Research, Activation Analysis, Nuclear Engineering, and Education. From the curve it was evident that the Research activities of these accelerators was definitely on the upswing, Nuclear Engineering applications have steadily fallen off while activation analysis and educational requirements have remained essentially constant since early 1963.

* Supported in part by a grant from the National Science Foundation.

**On leave from the Oak Ridge Associated Universities, Oak Ridge, Tennessee

I have been quite interested since 1964 in the curve that relates to the educational activities of these accelerators. It is my hope that it will be possible to give some positive slope to the educational curve. One rather discouraging bit of information is that there seems to be a falling off in federal support for these educational activities. This fall-off is particularly evident in the schools which offer only a bachelors degree. The AEC in 1960-61 gave about 3.5 million dollars in equipment grants. By 1965-1966 this amount had fallen to slightly over one million dollars. The NSF program of the same nature reached a peak in 1964 (about 9 million) and has steadily fallen to a value of about five million in 1967. A rather complete analysis of the trends for federal support in undergraduate nuclear education is given by Dr. Elmer Nussbaum in Ref. 1.

On the bright side of the picture is the fact that many of the accelerator and component manufacturing companies are now offering options on their equipment which is specifically designed for educational use in nuclear laboratories. This means the companies are hopeful that the trends in support will change. Their hope is probably based, at least to some extent, on discussions with the funding agencies. It has been my experience that many teachers are quite resourceful in obtaining equipment if they are convinced that they need that particular item. The selling job of the "Accelerator

Nuclear Educational Experiments" is therefore left up to the manufacturer and the resourcefulness of getting the funds belongs to the teacher.

The basic division of experiments which can be done on the undergraduate level falls into two categories. In the first group are the neutron experiments or experiments in which the accelerator must be used as a neutron generator with either the $T(d,n)^4He$ or the $D(d,n)^3He$ reactions. These neutron experiments would include neutron elastic and inelastic scattering, neutron-time-of-flight, total neutron-cross-section measurements, activation analysis, n-2n cross sections, neutron detector calibration, neutron attenuation measurements and shielding studies, neutron capture, the binding energy of the deuteron and numerous other experiments. The Charged Particle Experiments would include; Q value determination, (p,γ), (α,γ), charged particle coincidence and cross section measurements, kinematic studies, (d,p) and $(d,p'\gamma)$ studies, (p,α) reactions and a host of elastic scattering experiments.

Many of these experiments have been written up for the open literature or are available upon request from the manufacturers (see for example Ref. 2 through 5).

In this paper I will (a) outline the basic features of a few charged particle coincidence experiments, (b) discuss in general, elastic scattering with small accelerators, and (c) show the details of a simple neutron time-of-flight and total neutron cross-section experiment. Before discussing the experiments there will be a brief section on scattering chambers which is followed by some notes on targetry for accelerator experiments.

Scattering Chambers

The scattering chamber that was used for the charged particle experiments in this report is shown in figures 1, 2 and 3. It is a cylinder which is 15 inches in diameter by 7 inches deep. It has a glass top so that the students can see inside the chamber. This feature is not necessary but it is convenient for demonstrations and beam line-up procedures. The beam will fluoresce when it strikes many targets and the profile can be observed from above. A note of caution is in order at this point. It is possible to produce a sizable neutron background when deuterons are being accelerated. These neutrons are made from the $D(d,n)^3He$ reaction when deuterons strike the walls and defining apertures in the vacuum system. It is best to keep a monitor available at all times so that background levels can be determined before working in an area. Some electronic type monitors do not function properly in a room if there is present a corona discharge from the high voltage. Under these conditions it is possible to falsely read high backgrounds with

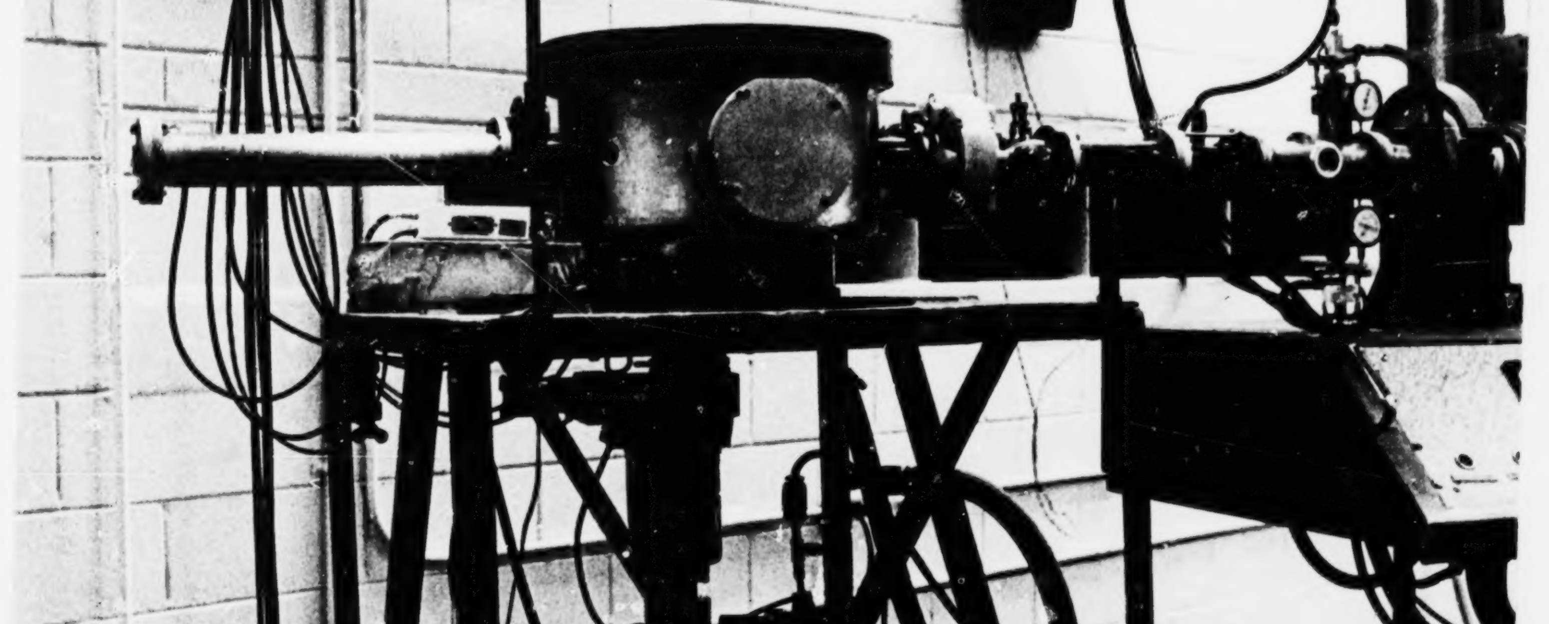

FIGURE 1. Side View of the Scattering Chamber Used for the Measurements in this report.

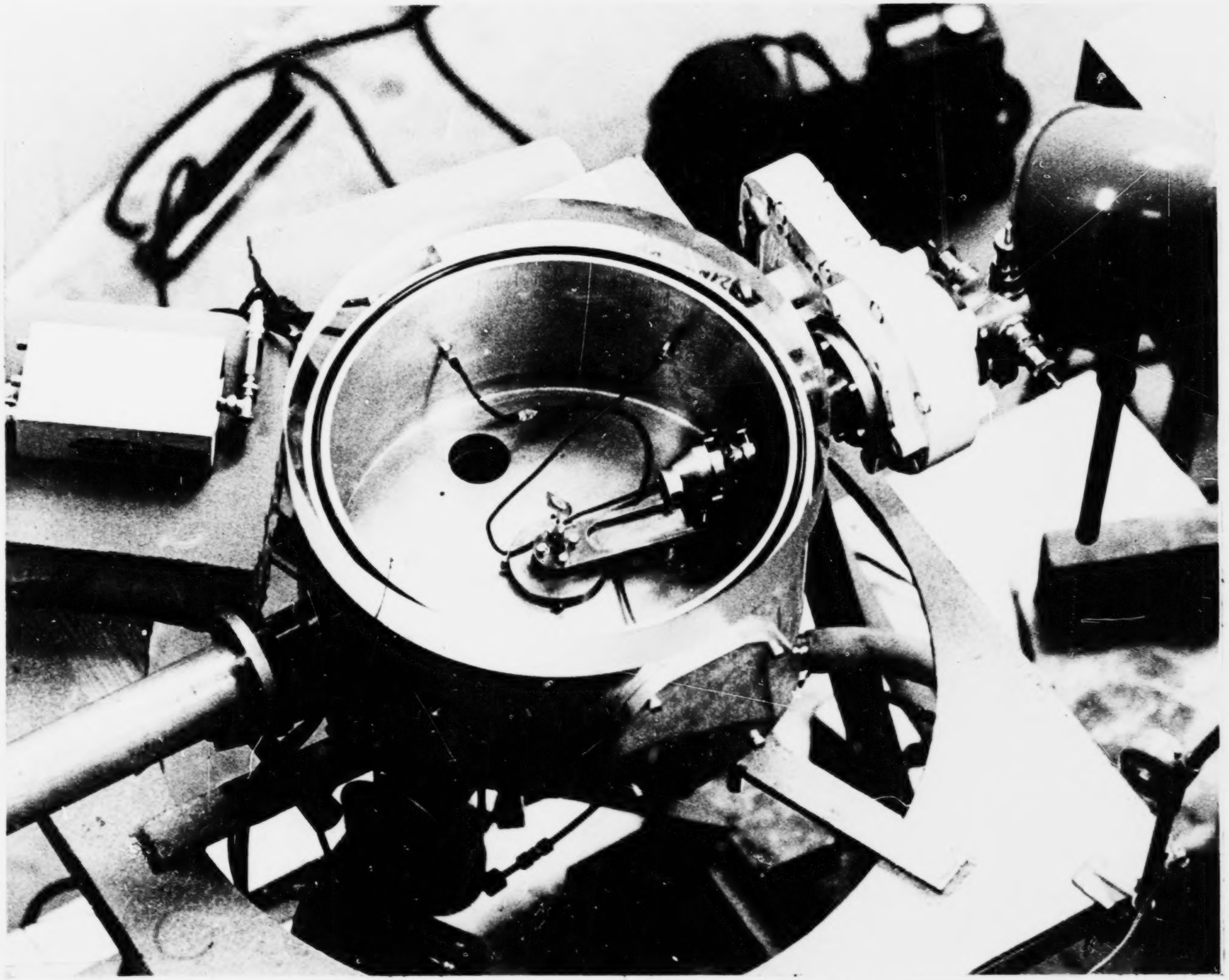

FIGURE 2. Top View of the Chamber Discussed in Figure 1.

these meters, when the real background is very low. An excellent review of the Health Physics problems with small accelerators can be found in a paper by J. Berger et al in Ref. 1. For the charged particle experiments the beam current is usually kept to a value of less than 1 μamp and hence the radiation problem is minimized.

The pumping system for the scattering chamber consisted of a 2 inch air-cooled diffusion pump followed by a fore pump. For many accelerators it might not be necessary to have a separate pumping system for the scattering chamber. The operating pressure in the scattering chamber should be 2×10^{-5} mm. of Hg. or better.

There are provisions in the chamber for one movable detector and five fixed detectors. For some experiments (for example multiparticle break-up reactions) it would be convenient to have two independently movable detectors.

It has been estimated that the above scattering chamber could be constructed in a one man machine shop in a total time of about six weeks.

For the person who is interested in building a scattering chamber many good references are available (see for example Ref. 6 through 12).

Commercial Availability of Scattering Chambers

Figure 4 shows the educational scattering chamber which is offered by ORTEC, Inc., Oak Ridge, Tennessee.

In Figure 5 is shown the chamber which is sold by High Voltage Engineering Corp., Burlington, Mass., in conjunction with their Accelerator Nuclear Physics Course

Targets for Accelerator Experiments

Any of the charged particle type of experiments that can be done with a small accelerator requires a suitthin target. Targetry is a field all to its own and in many cases is more of an art than a science. Fortunately, the target preparation for the experiments that will be discussed in this paper does not present a real problem.

With a low energy accelerator (less than 400 KeV) it is rather difficult to produce nuclear reactions on target nuclei which are heavier than ^{31}P. The reason for this difficulty of course, is the Coulomb barrier. Many of these thin targets cannot be produced as self-supported foils and hence must be evaporated onto some suitable substrait. The most common substrait materials that the author has used are carbon and nickel. The methods of preparing these substrait materials will be briefly outlined.

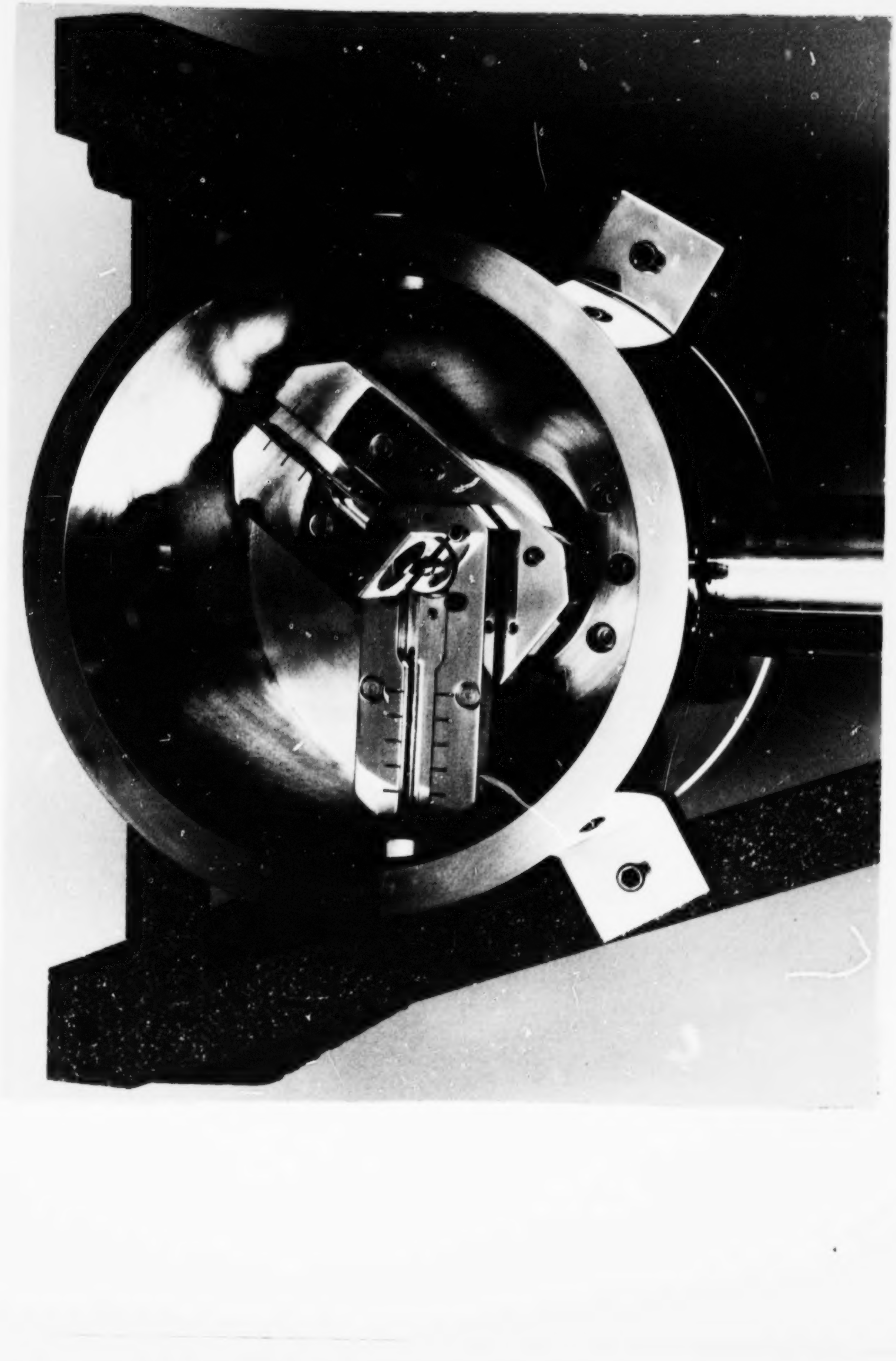

FIGURE 4. ORTEC Educational Scattering Chamber.

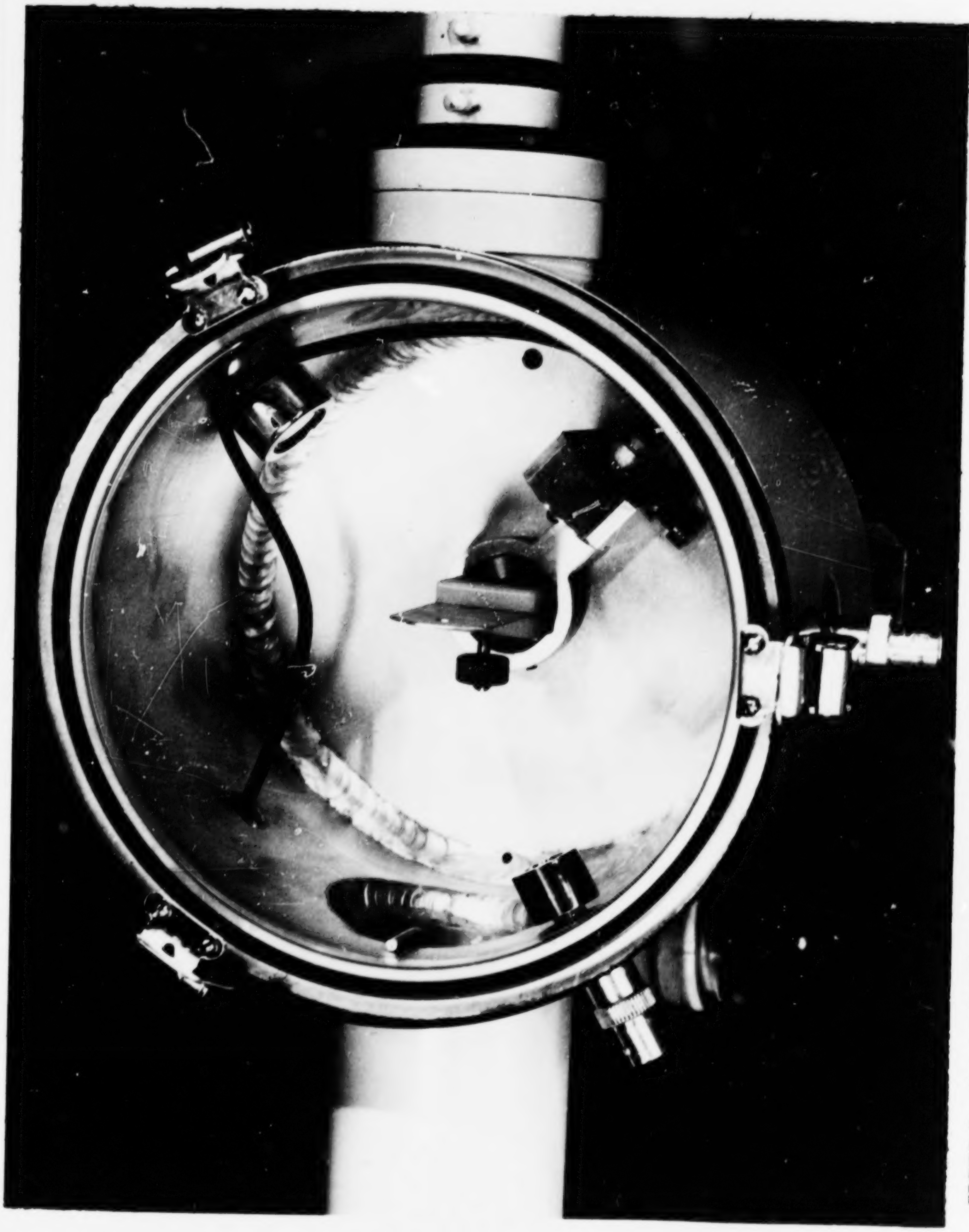

FIGURE 5. Scattering Chamber for Accelerator Nuclear Physics Course, High Voltage Engineering Corporation.

Carbon Foils

Carbon foils can be purchased from several manufacturers. The thicknesses available are from 2 $\mu gm/cm^2$ to 500 $\mu gm/cm^2$. The foils are usually shipped to the purchaser on glass slides. Detailed instructions are provided for floating the foils off of the glass slides and picking them up on the target frame. With some practice it is quite easy to produce acceptable carbon targets.

For the $^{12}C(p,p)^{12}C$, $^{12}C(d,d)^{12}C$, $^{12}C(\alpha,\alpha)^{12}C$ and $^{12}C(^{3}He,^{3}He)^{12}C$ reactions which will be discussed in this paper, the carbon targets should be about 25 $\mu gm/cm^2$. The reason for using such a thin target is that the Rutherford cross-section is large enough even at the back angles so that counting statistics are easy to get with these thin targets. The other point is that the $\frac{dE}{dX}$ of the projectile must be integrated over the target thickness to obtain the energy loss of the projectile in the target. If the target is too thick the spread in the pulse height spectrum will make it difficult to analyze.

For substrait material the carbon foils should again be about 25 $\mu gm/cm^2$. Experience has shown that it is difficult for the novice (though not impossible) to evaporate onto a foil much thinner than this. The reason for this difficulty is that the heat from the evaporating filament tends to break most of the foils, if they are much thinner than 25 μgm/cm^2. Materials have been evaporated onto 5 μgm/cm^2 carbon foils but it is not recommended that this feat is attempted until considerable experience has been obtained in the art of targetry.

Carbon foils which are coated on glass slides and ready for the float off procedure can be obtained from the following sources:

1. Isotopes Division of the Oak Ridge National Laboratory.
2. High Voltage Engineering Corp., Burlington, Mass.
3. Yissum Research Development Corp., Hebrew University, Jerusalem Israel

Nickel Foils

Nickel foils make a suitable substrait and can also be used for the ^{58}Ni(p,p)^{58}Ni(d,d)^{58}Ni and ^{58}Ni(α,α)^{58}Ni reactions. The only commercial manufacturer of these research grade foils is The Chromium Corp. of America, Waterbury, Connecticut. The foil thicknesses which are applicable for targetry in this energy range are from 3 micro-inch to 10 micro-inch. These foils are shipped with a 1 x 10^{-4} in. copper backing. The nickel has been electro-deposited onto the copper. Instructions are provided for etching away the copper. The general procedure used is as follows: 1. The nickel side of the

foil is attached to the target frame with epoxy or glyptal.
2. The copper is etched away leaving the self-supported nickel foil.

The author's general feeling is that the 5 microinch nickel foil is perhaps the best for all-around use.

Gold Foil

Gold foil for either substrait use or for the $^{197}Au(p,p)^{197}Au$ and $^{197}Au(d,d)^{197}Au$ reactions can be provided from many sources. Hammered gold leaf of the type used for electroscopes can be mounted (with some practice) onto target frames. The Yissum Research Corp. mentioned above will supply gold and aluminum foil which has been evaporated onto glass slides. These foils are floated off in a manner similar to that described for the carbon foils. Gold foil for the Rutherford scattering should be about 100 μgm/cm^2.

^{6}Li and ^{7}Li Targets

Lithium flouride can easily be evaporated onto a suitable substrait to provide either a lithium or a flourine target. For the $^7Li(p,\alpha)\alpha$ and $^6Li + d$ reactions, which will be described in this paper, targets of about 100 μgm/cm^2 Lithium Flouride were used.

Additional Target Information

Commercial Sources

In the literature there are many publications with regard to target fabrication. Reference 1 (a paper by E. H. Kobisk in the Proceedings) gives an excellent overview of the current techniques. Other reports and publications with regard to targetry can be found in the literature (Ref. 13 through 32). Of recent, Nuclear Instruments and Methods, and The Review of Scientific Instruments are the two journals in the open literature that seem to carry papers that deal with targetry.

Hastings and Co., Inc., 2314 Market St., Philadelphia, Pa., can provide gold, aluminum and silver foil in a range of thicknesses from 6.5×10^{-6} inches to 1.5×10^{-4} inches.

High Purity metalic foils of most metals can be obtained from A. D. Mackay, Inc., 198 Broadway, N.Y., N.Y., 10038. The thicknesses available are from 5×10^{-5} inches and up.

The Atomic Energy Research Establishment, Harwell Didcot Berks, England, sells targets for nuclear research. The particular group providing this service is the Electromagnetic Separation Group B.7.

The Isotope Development Center of the Oak Ridge National Laboratory, Oak Ridge, Tennessee, provides the greatest variety of targets for charged particle, gamma ray, and neutron studies. Table 1 (see Appendix) is a rather complete listing which gives the targets available from this group. (Taken from the paper by E. H. Kobisk in Ref. 1).

Target Thickness and $\frac{dE}{dX}$ Calculations

The accuracy with which a differential cross-section can be measured is for the most part dependent upon how well the target thickness is known. For the Rutherford Scattering experiments or the nuclear reactions in which the target is a self-supported foil, the target thickness is easily determined to plus or minus 25%. One method in which the thickness can be determined is by the weighing technique. By this method a thin metal disk is carefully weighed before evaporation. It is placed in the evaporator as close as possible to the targets that are being made. After evaporation the disk is again carefully weighed. The target thickness can thus be determined in this manner. The targets are assumed to have the same thickness as the blank. If the targets are at least 12 inches from the boat, this seems to be a pretty good assumption. This same technique can be used to determine a target thickness when the material is being evaporated onto a substrait. The thicknesses of the commercial foils of carbon, nickel, gold and aluminum are usually given with an accuracy of plus or minus 35%.

The other method of determining an unknown foil thinkness is by alpha gauging the foil. In using this method alpha particles from some suitable radioactive source are allowed to pass through the foil. The energy loss of the alphas is measured and the $\frac{dE}{dX}$ tables (Ref.33 through 37) are used to calculate the target thickness. Reference 36 is particularly good since it is economical ($\sim$\$6) and in it $\frac{dE}{dX}$ calculations are made for 74 different materials.

The scattering chamber provides an excellent place for the foil thickness determinations by alpha gauging. In fact many charged particle detector experiments can be performed in the scattering chamber independent of the accelerator. Five such experiments have been written up for the open literature (Ref. 38). If all other parameters are known, the Rutherford Scattering can be used to determine an unknown target thickness. This can be accomplished either in an absolute or a relative fashion.

In the next section a few experiments will be outlined and their connection with this section on targetry will be made.

Charged Particle Coincidence Experiments

In this section and all of those to follow it is assumed that the reader is familiar with the basic electronics which are used with semiconductor detectors. For those who feel a review is needed Ref. 38 through 44 provide a good place to start.

The term Charged Particle Coincidence Experiments, as used here means coincidence experiments between two of the charged particles that emerge from a nuclear reaction. Because of the Coulomb barrier (and for low voltage accelerators) a definite limitation is placed on the reactions that can be studied. The Q value for the reaction must be fairly high. The reactions which seem to fit into this category are the following: $^{6}Li(d,\alpha)^{4}He$ Q = 22.37 MeV, $^{6}Li(p,^{3}He)^{4}He$ Q=4.02 MeV, $^{7}Li(p,^{4}He)^{4}He$ Q=17.34 MeV and $D(^{3}He,p)^{4}He$ Q=18.351 MeV. The last reaction listed is a little more difficult to study because of the targetry problem. These points will be discussed later.

Figure 6 is an electronic block diagram which shows the accelerator geometry. Alpha particles from $^{7}Li(p,\alpha)\alpha$ reactions are being studied with the circuitry in the figure. The beam (∿500 nano-amps) is defined to a rectangular spot (1 mm x 1mm). The ^{7}LiF target thickness was about 100 μgm/cm^{2}. The detectors subtended a solid angle of 1×10^{-2} steradians with respect to the target. The thin copper foil (1×10^{-4} in) in front of

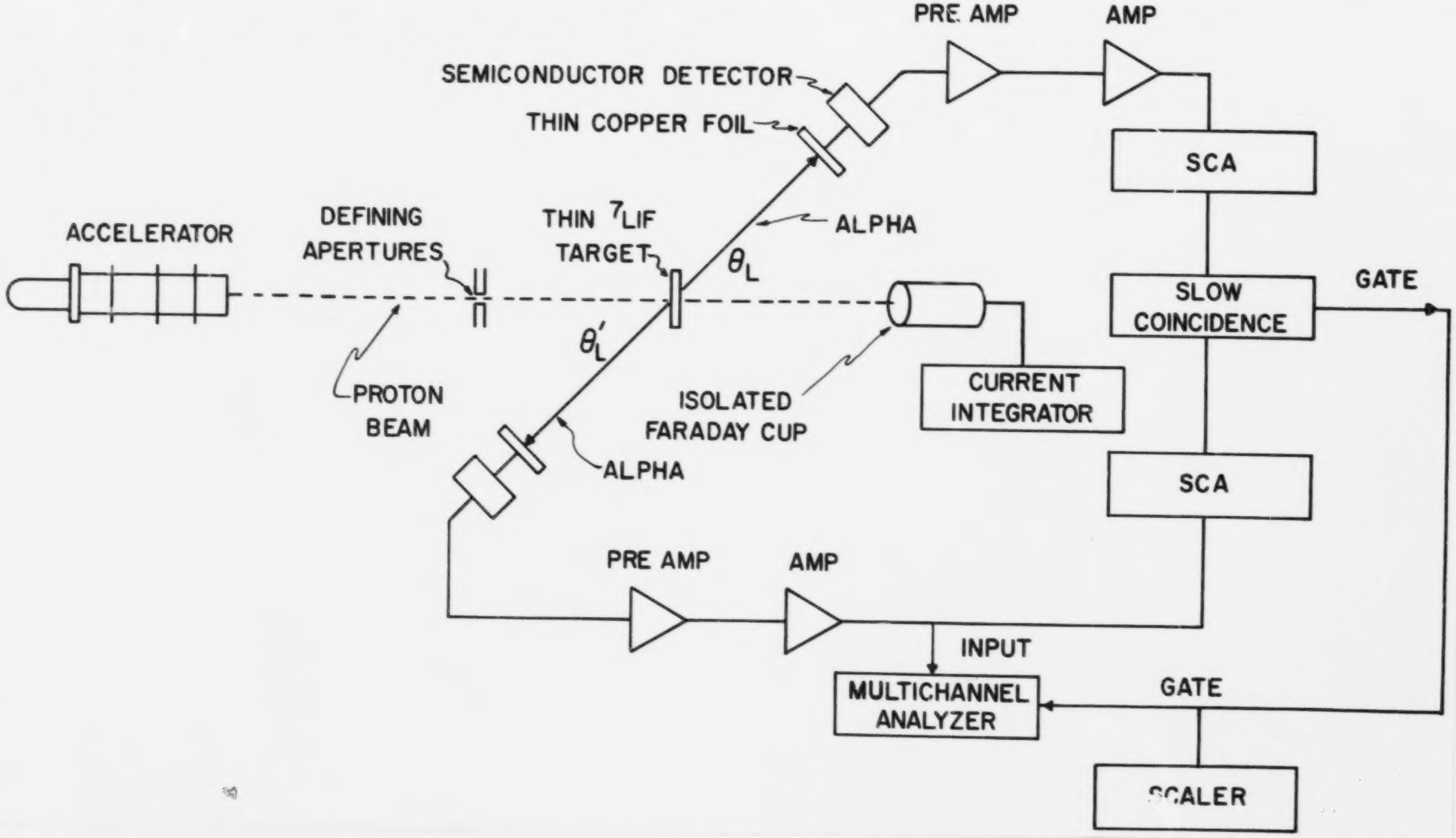
PRE AMP
AMP
SEMICONDUCTOR DETECTOR
THIN COPPER FOIL
SCA
ACCELERATOR
DEFINING APERTURES
THIN ^{7}LIF TARGET
ALPHA
θ_L
SLOW COINCIDENCE
GATE
θ'_L
PROTON BEAM
ISOLATED FARADAY CUP
CURRENT INTEGRATOR
ALPHA
SCA
PRE AMP
AMP
INPUT
MULTICHANNEL ANALYZER
GATE
SCALER

FIGURE 6. Experimental Configuration for the Study of Charged Particle Coincidence Experiments.

the detectors completely stopped all of the elastically scattered protons from the target. This was necessary at these low energies (∿150 KeV) since the elastics would have flooded all of the electronic circuits, with the given geometry. The output of either of the amplifiers in the figure would show a single isolated alpha group whose energy is about 8.5 MeV. The energy versus angle dependence for this reaction is shown in Figure 7. The single channel analyzers in Figure 6 are set in the differential mode, with E=5 MeV and ΔE=10 MeV. Because of the kinematics for the $^{7}Li(p,\alpha)\alpha$ reaction the two alpha particles should theoretically emerge from the target with an angular separation (in the center of mass system) of 180°. Hence if one detector is fixed and the other one is varied as a function of θ the Coincidence overlap spectrum can be measured. If the number of counts in the scaler (Figure 6) is plotted as a function of the angular separation of the two alpha particles, the curve should show a maximum at 180°. This experiment is similar in nature to the proof that annihilation radiation from position emitters leaves the source with 180° separation. The annihilation experiment is usually done with scintillation detectors a ^{22}Na source and electronics similar to Figure 6.

If the ^{7}LiF target in Figure 6 is replaced with a ^{6}LiF target the $^{6}Li(p,{}^{3}He){}^{4}He$ reaction can be studied. The Q value for the reaction is 4.02 MeV. Hence the

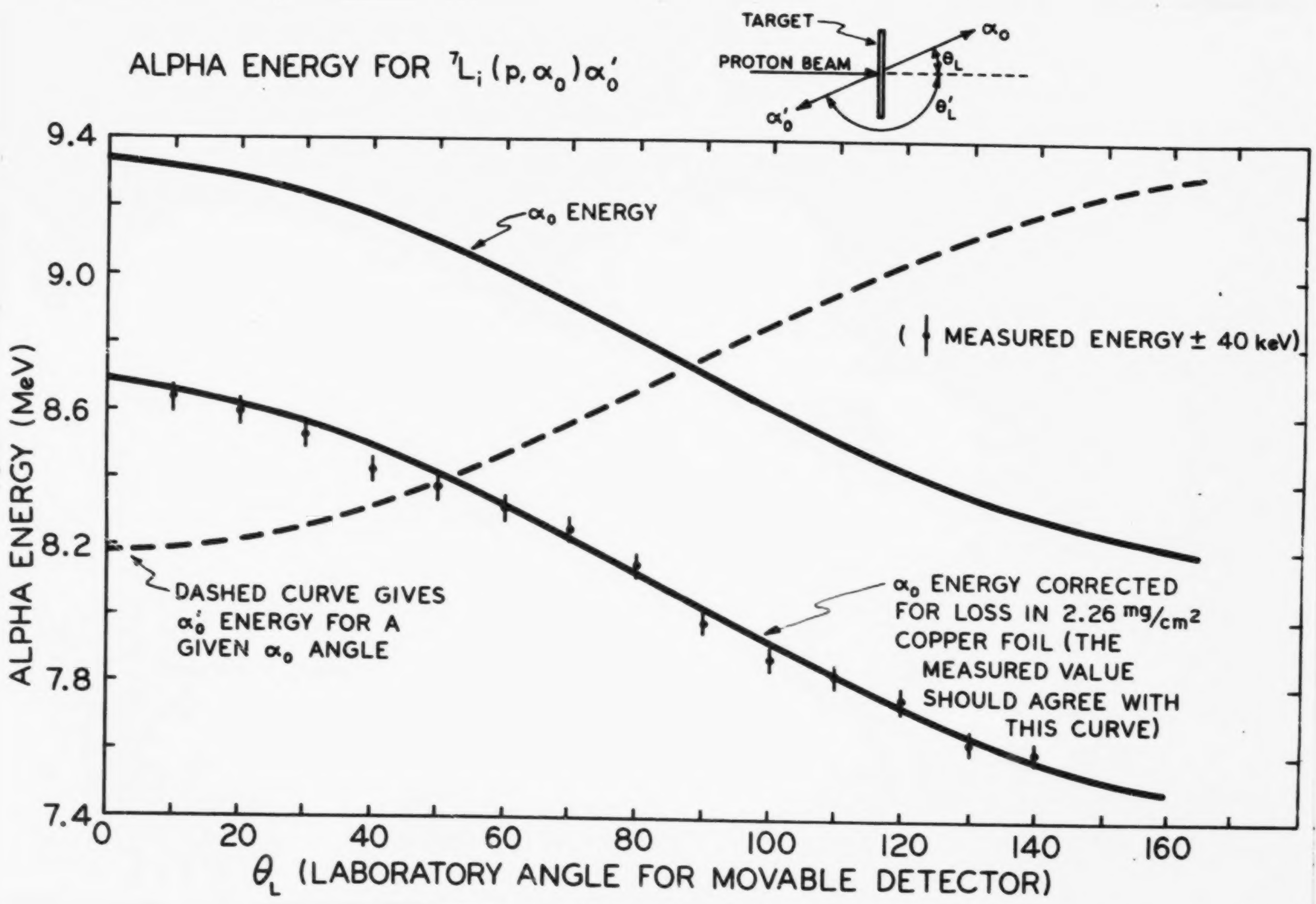

FIGURE 7. Kinematic Calculations and Experimental Points for the ^{7}Li(p,α) α Reaction at an Incident Proton Energy of 150 keV.

alpha and the ^{3}He particle will share this energy in keeping with the kinematics for the reaction. Experimentally this means that single channel windows would have to be set at E=.5 MeV and $\Delta E=3$ MeV. Otherwise, the format would be identical to that described for the ^{7}Li(p,α)α reaction. In Figure 8 is shown a pulse height spectrum which was taken from one of the amplifiers in Figure 6.

An analysis of the ^{7}Li(p,α)α reaction would show $^{7}\mathrm{Li}+p\rightarrow{}^{8}\mathrm{Be}\rightarrow\alpha+\alpha$. It is also possible to form ^{8}Be in the following manner $^{6}\mathrm{Li}+d\rightarrow{}^{8}\mathrm{Be}\rightarrow\alpha+\alpha$. The pulse height spectrum which results from a 100 μgm/cm^{2} ^{6}LiF target when it is bombarded with a 500 nano-amp deuterium beam is shown in Figure 10. Note that in addition to the alpha particle (group D) there are two proton groups from the ^{6}Li(d,p)^{7}Li reaction. The coincidence overlap spectrum for the two alpha particles is measured as it was in the two previous cases.

The pulse height spectrum for the D(^{3}He,p)α reaction is shown in Figure 9. The Q value for the reaction is 18.351 MeV. It can be seen in Figure 9 that the proton carries off most of the energy ($\sim$15 MeV). The detector which is used to stop the proton should have a depletion depth of $\sim$2000 microns of silicon. Thin deuterium targets can be fabricated by performing an RF discharge in a deuterated Acetylene atmosphere. The deuterium is cracked out in the discharge as a thin polymer

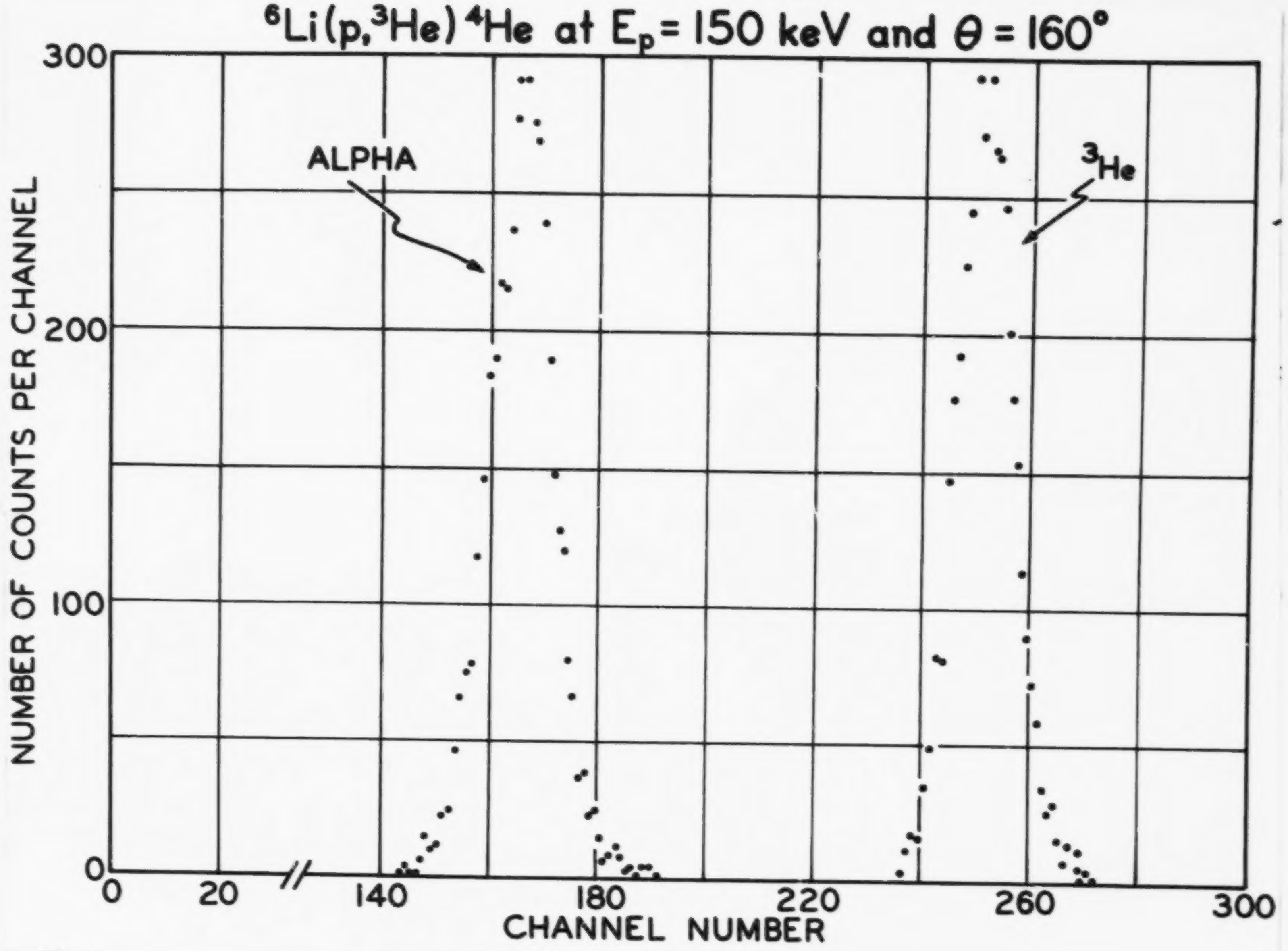

FIGURE 8. Pulse Height Spectrum for the $^6Li(p,^3He)\,^4He$ Reaction at an incident Proton Energy of 150 keV and a laboratory angle of 30°.

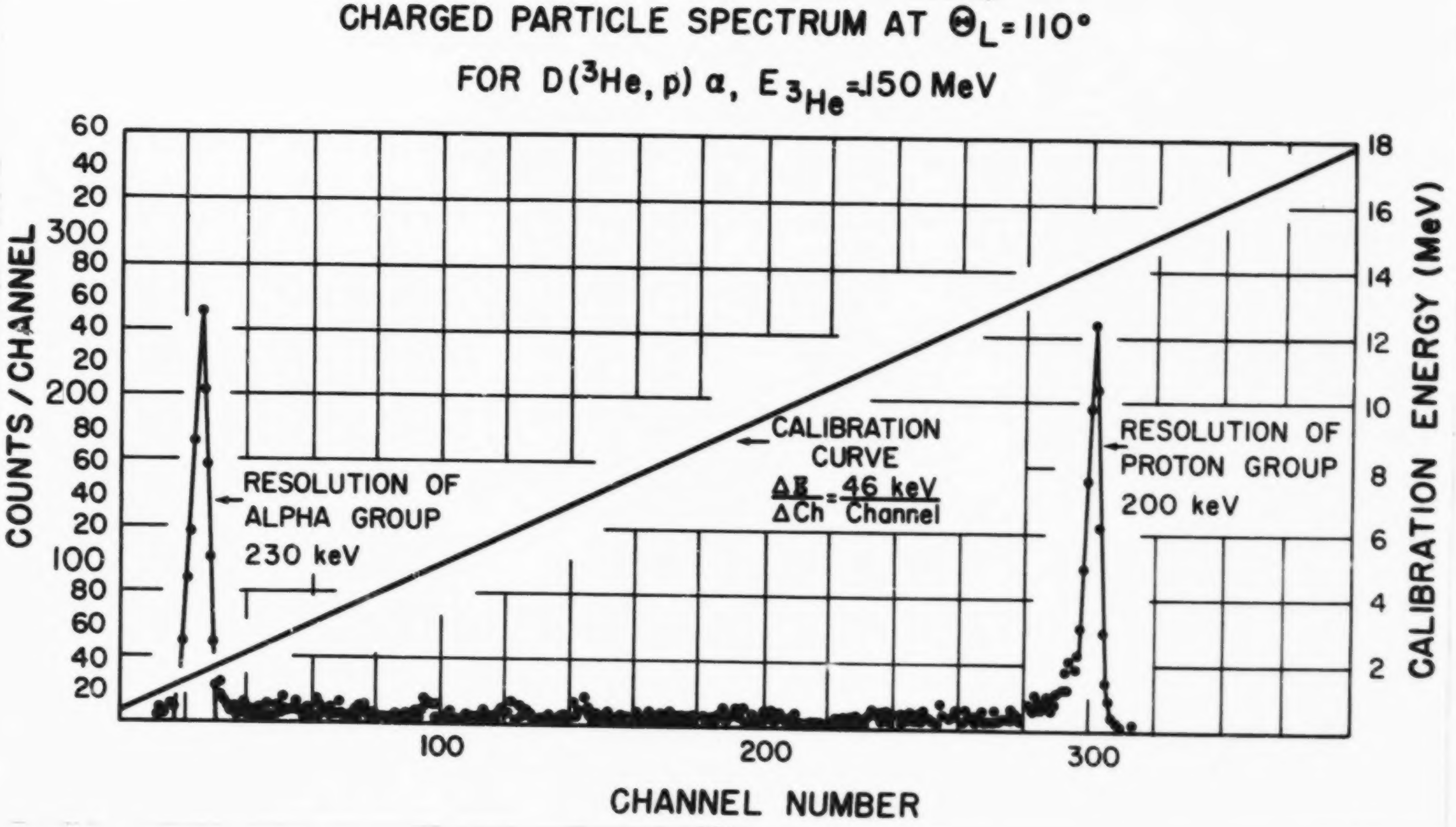

FIGURE 9. Pulse Height Spectrum for the $D(^3He,p)\alpha$ Reaction with the Energy Calibration Curve.

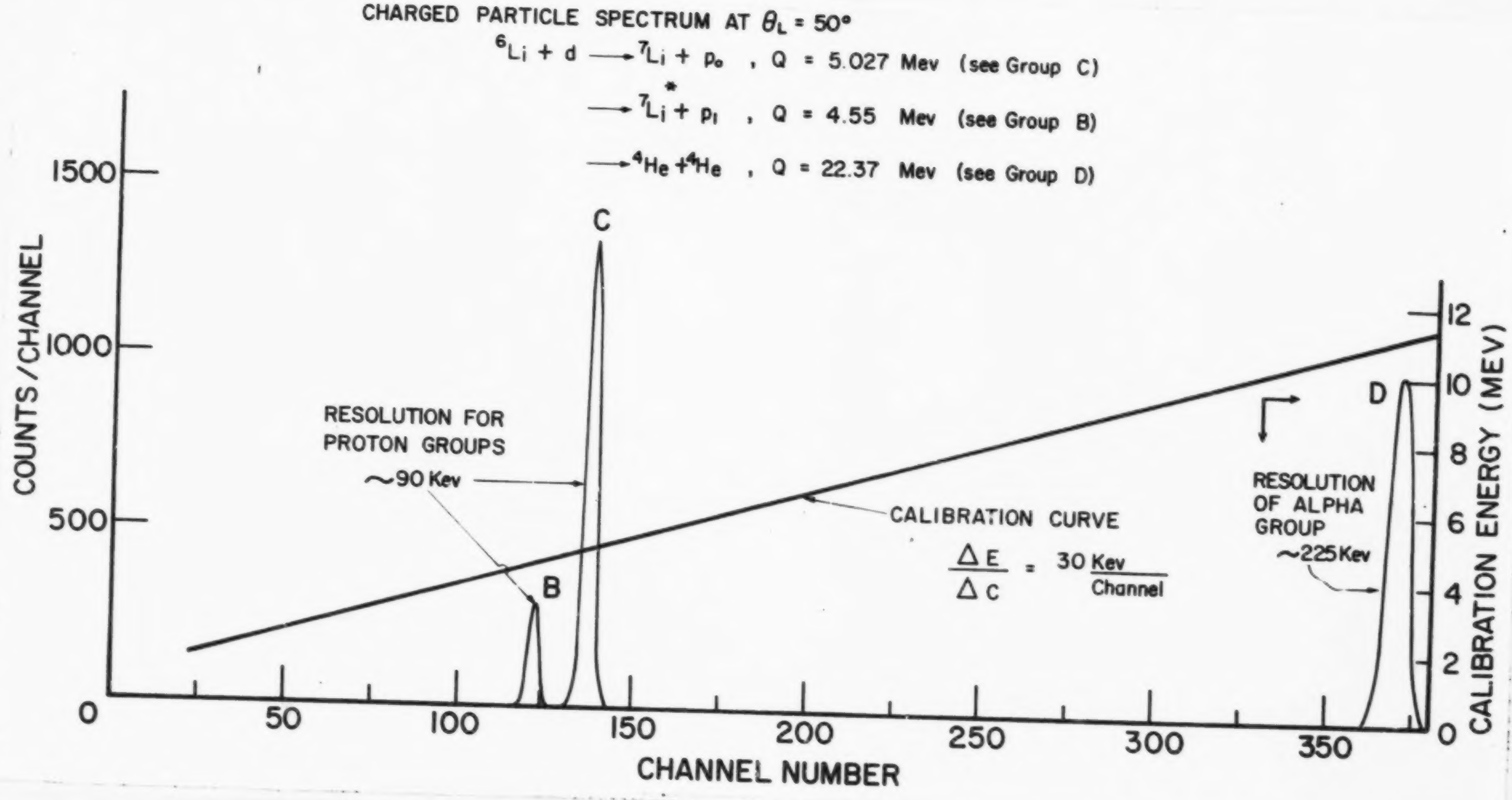

FIGURE 10. Charged-particle spectrum at $\theta_L = 50^o$ for the $^6Li(d,p)\ ^7Li$ and $^6Li(d.\alpha)\ ^4He$ reactions at a deuteron energy of 150 keV. Resolution for proton groups are 90 keV. Resolution of alpha group are 225 keV. $\Delta E/\Delta C$ = 30 keV/channel. Group C: Q = 5.027 MeV. Group B: Q = 4.55 MeV. Group D: Q = 22.37 MeV.

which can be deposited onto thin carbon foils. The author can provide a more detailed write-up for anyone who is interested in making these targets. The coincidence overlap measurements for the D(^{3}He,p)α reaction is similar to the other cases which were treated above.

In addition to the charged particle coincidence experiments which are outlined above many other fundamental measurements can be made on the four reactions listed. For example, the energy versus angle (Kinematic relations) can be determined for both of the emerging particles. In Figure 7 the solid curve (top) represents the theoretical E versus θ curve for the ^{7}Li (p,α)α reaction. The bottom solid curve shows these energies that have been corrected for the (dE) of the alphas in the 2.26 mg/cm^2 foil that was used to shield out the elastics. These corrections were made by using the data in Table II.

TABLE II

ENERGY LOSS OF α-PARTICLES IN A 2.26 mg/cm^2 COPPER FOIL
(From Ref. 36)

E	$\frac{dE}{dX}$ $\frac{\text{keV cm}^2}{\text{mg}}$	E(keV)
10.00	289	655
9.75	291	657
9.50	292	660
9.25	294	665
9.00	296	670
8.75	305	690
8.50	309	700
8.25	316	715
8.00	325	735

From Table II:

$$dE = \frac{dE}{dX}\ (\mathrm{KeV}\frac{cm^2}{mg}\ \text{x foil thickness}\ (mg/cm^2)$$

After the corrections have been made for energy loss in the foil, the Q value for the reaction can be determined.

From conservation of energy for the $^7Li(p,\alpha_o)\alpha_o'$ reaction:

$$Q=E_{\alpha o}+E_{\alpha_o'}-Ep.$$

When the values from Figure 7 were used in the above equation, the experimental Q value for the reaction was 17.36 MeV. The accepted value is 17.347 MeV (Ref. 58).

Many other measurements (Ref. 45 through 57) can be made on this reaction and others at these low energies. They are too numerous to mention in this paper.

The ^6Li+d reaction can also be used to study the excited states of ^7Li and ^7Be. When ^6Li is bombarded with low energy deuterons the following reactions take place with appreciable cross-section:

1. $^6Li(d,p,)^7Li^*;\ ^7Li^*\rightarrow{}^7Li+\gamma(0.478\ MeV)\ Q=4.55\ MeV$
2. $^6Li(d,p_o)^7LiQ=5.027\ MeV.$
3. $^6Li(d,\alpha)^4HeQ=22.37\ MeV.$
4. $^6Li(d,n_1)^7Be^*;\ ^7Be^*\rightarrow{}^7Be+\gamma(0.431\ MeV)Q=2.95\ MeV.$
5. $^6Li(d,n_o)^7Be;\ Q=3.38\ MeV.$

Figure 11 shows the electronics that would be used to study these reactions. Figure 11(a) is the configuration for

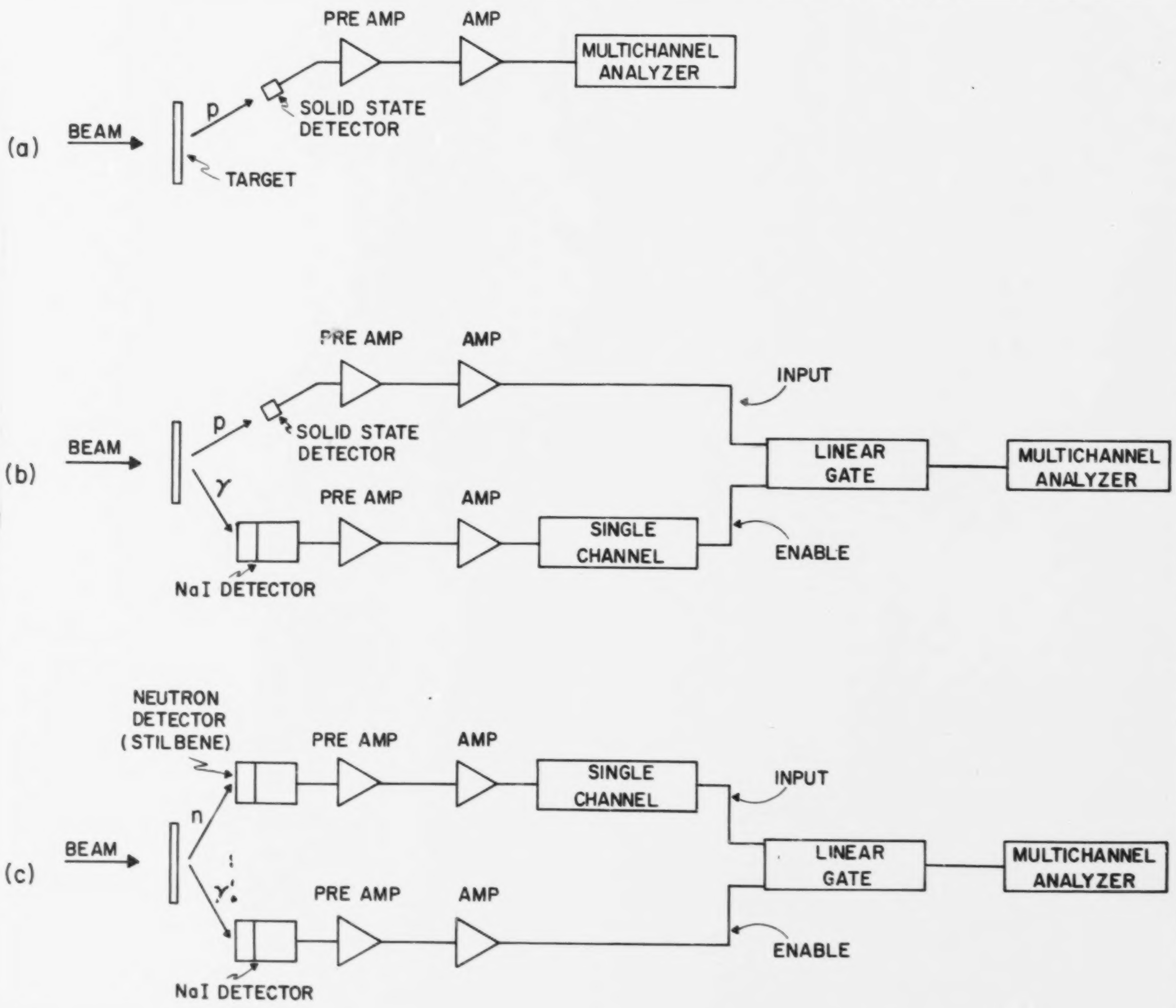
(a)
BEAM
p
TARGET
SOLID STATE DETECTOR
PRE AMP
AMP
MULTICHANNEL ANALYZER
(b)
BEAM
p
γ
SOLID STATE DETECTOR
NaI DETECTOR
PRE AMP
AMP
PRE AMP
AMP
SINGLE CHANNEL
INPUT
ENABLE
LINEAR GATE
MULTICHANNEL ANALYZER
(c)
BEAM
n
γ'
NEUTRON DETECTOR (STILBENE)
NaI DETECTOR
PRE AMP
AMP
SINGLE CHANNEL
PRE AMP
AMP
INPUT
ENABLE
LINEAR GATE
MULTICHANNEL ANALYZER

FIGURE 11: Block diagram of the electronics. (a) Simple charged-particle spectrum. (b) Charged-particle spectrum with gamma coincidence requirement. (c) Gamma spectrum with neutron coincidence requirement.

just looking at the charged particle spectra from the reaction. If the gains were set properly the multichannel analyzer would show the pulse height distribution in Figure 10.

Figure 11(b) would be used to study the proton, γ coincidence as illustrated in Eq. 1 and 2 above. Figure 12 shows a charged particle spectrum without (top) and with (bottom) the coincidence gate requirement in Figure 11(b). A similar study can be made for Eq. 4 and 5 by using the electronics shown in Figure 11(c).

Elastic Scattering

There has been no experiment in the history of Nuclear Physics that has had a more profound impact than that of Rutherford Scattering (Ref. 59). It was Rutherfords analysis of this elastic scattering which gave us the first correct model of the atom.

Elastic scattering can easily be done with low voltage accelerators and a suitable scattering chamber. Several of these experiments have been written up in detail and are available in the open literature (see Ref. 60 and 61).

The basic electronic configuration for these measurements is shown in Figure 13. The theoretical expression for the elastic scattering cross-section is

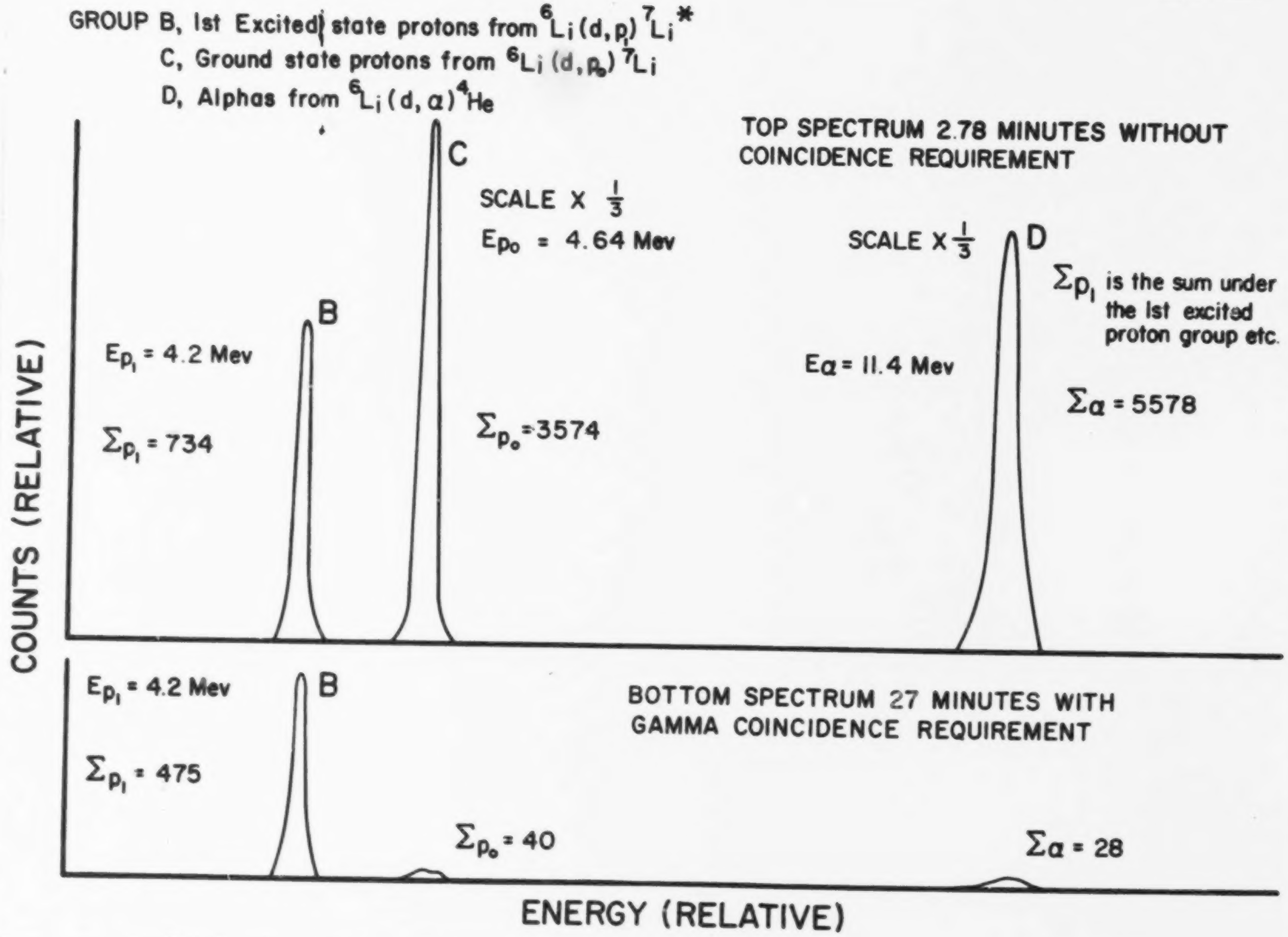

FIGURE 12. Charged-particle spectrum, (top) 2.78 min without and (bottom) 27 min with gamma coincidence requirement for the ^{6}Li(d,p) ^{7}Li and ^{6}Li(d,α) ^{4}He reactions at an incident-deuteron energy of 150 keV. Group B: first-excited protons from ^{6}Li(d,p) ^{7}Li*. Group C: Ground-state protons from ^{6}Li(d,p_o) ^{7}Li. Group D: alphas from ^{6}Li(d,α) ^{4}He.

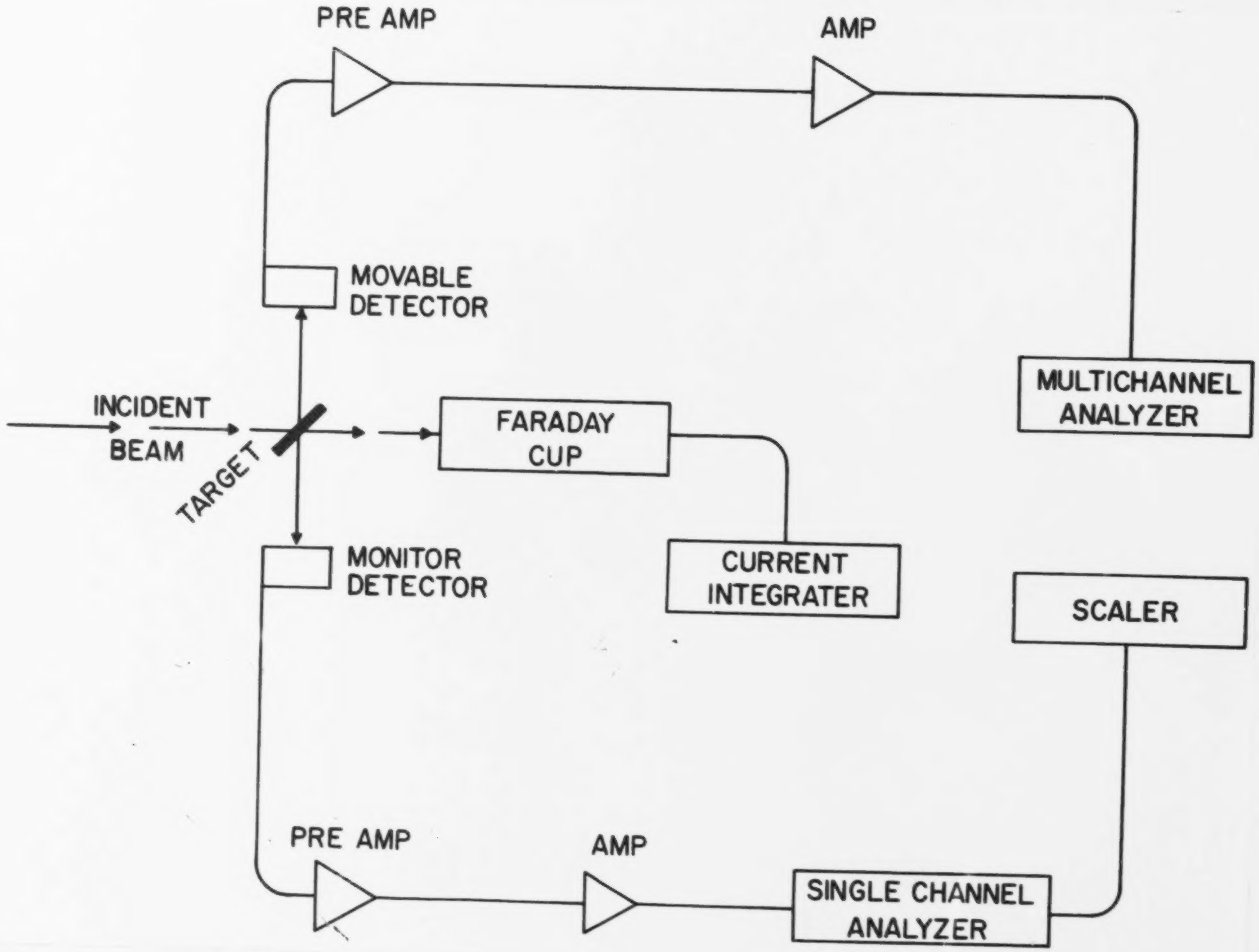
PRE AMP
AMP
MOVABLE DETECTOR
MULTICHANNEL ANALYZER
INCIDENT BEAM
TARGET
FARADAY CUP
MONITOR DETECTOR
CURRENT INTEGRATER
SCALER
PRE AMP
AMP
SINGLE CHANNEL ANALYZER

FIGURE 13. Electronic Block Diagram for the Elastic Scattering Experiment.

given by the following expression (Ref. 33 and 62):

$$\frac{d\sigma}{d\omega} \text{ (mb/sr)} = 1.296 \left[\left| \frac{Z_1 Z_2}{E} \right|^2 \csc^4 \frac{(\Theta)}{(2)} - \left| 2 \frac{M}{A} \right|^2 \right]$$

where Z_1 and Z_2 are the Atomic numbers of the projectile and target, E is the energy of the projectile in MeV. M and A are the mass numbers of the projectile and target nucleus.

If the electronics in Figure 13 are used the experimental cross-section is given by the following expression:

$$\frac{d\sigma\,(cm^2)}{d\Omega\,(sr)} = \frac{n}{N n_o \Delta\Omega}$$

where n is the number of counts from the movable detector system. (For example n would be the sum under the pulse height spectrum shown in Figure 14), N is the number of incident particles, n_o is the number of target nuclei/cm^2, and $\Delta\Omega$ is the solid angle of the movable detector in steradians.

Figure 15 shows the experimental points and the theoretical expression for the $^{12}C(d,d)^{12}C$ reaction.

If a current integrator is not available for determining N(in the above formula), it is possible to

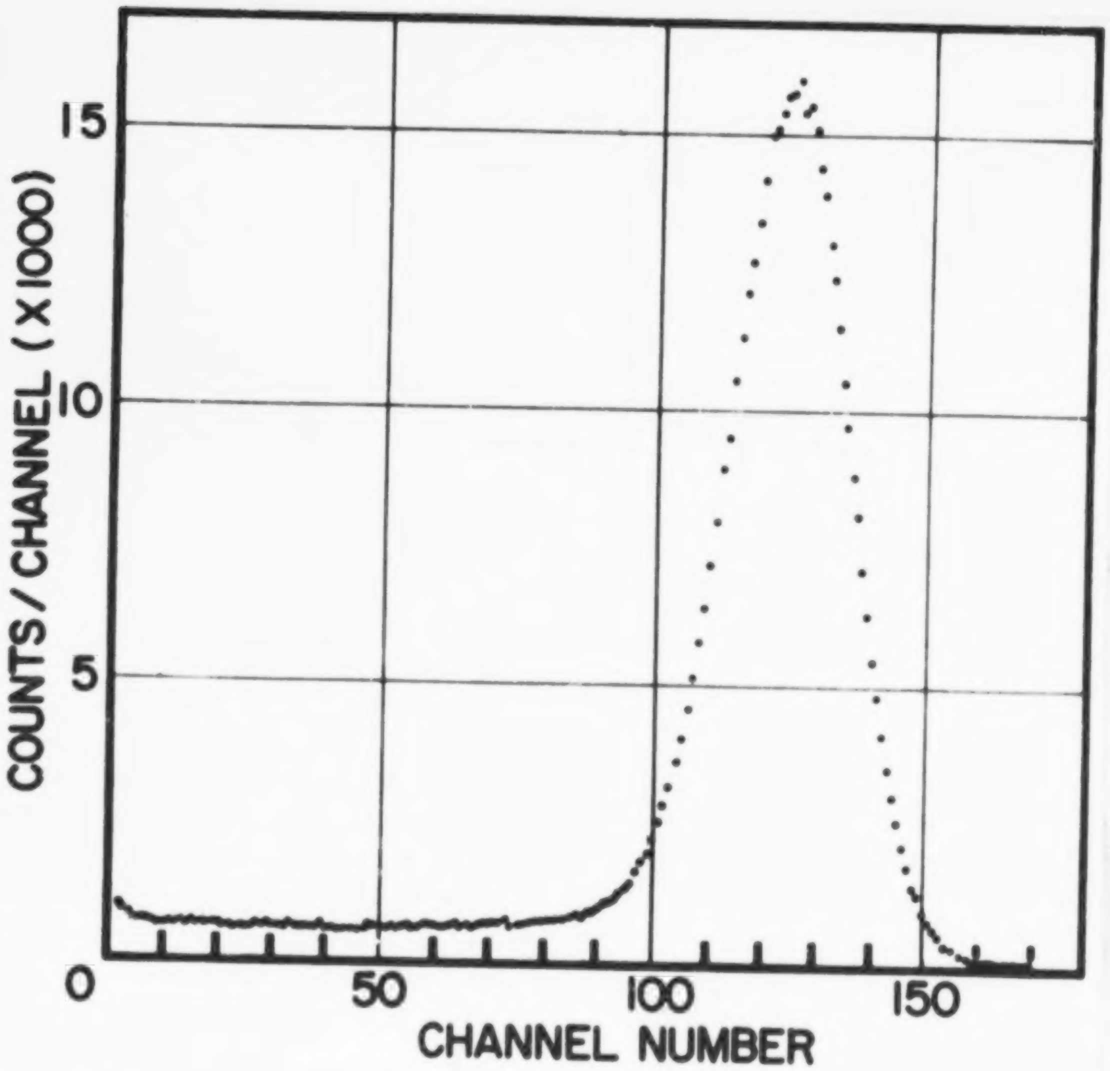

FIGURE 14. Pulse-height spectrum for monitor detector system for the $^{12}C(p,p)^{12}C$ reaction at an incident proton energy of 150 keV and a laboratory angle of 30°.

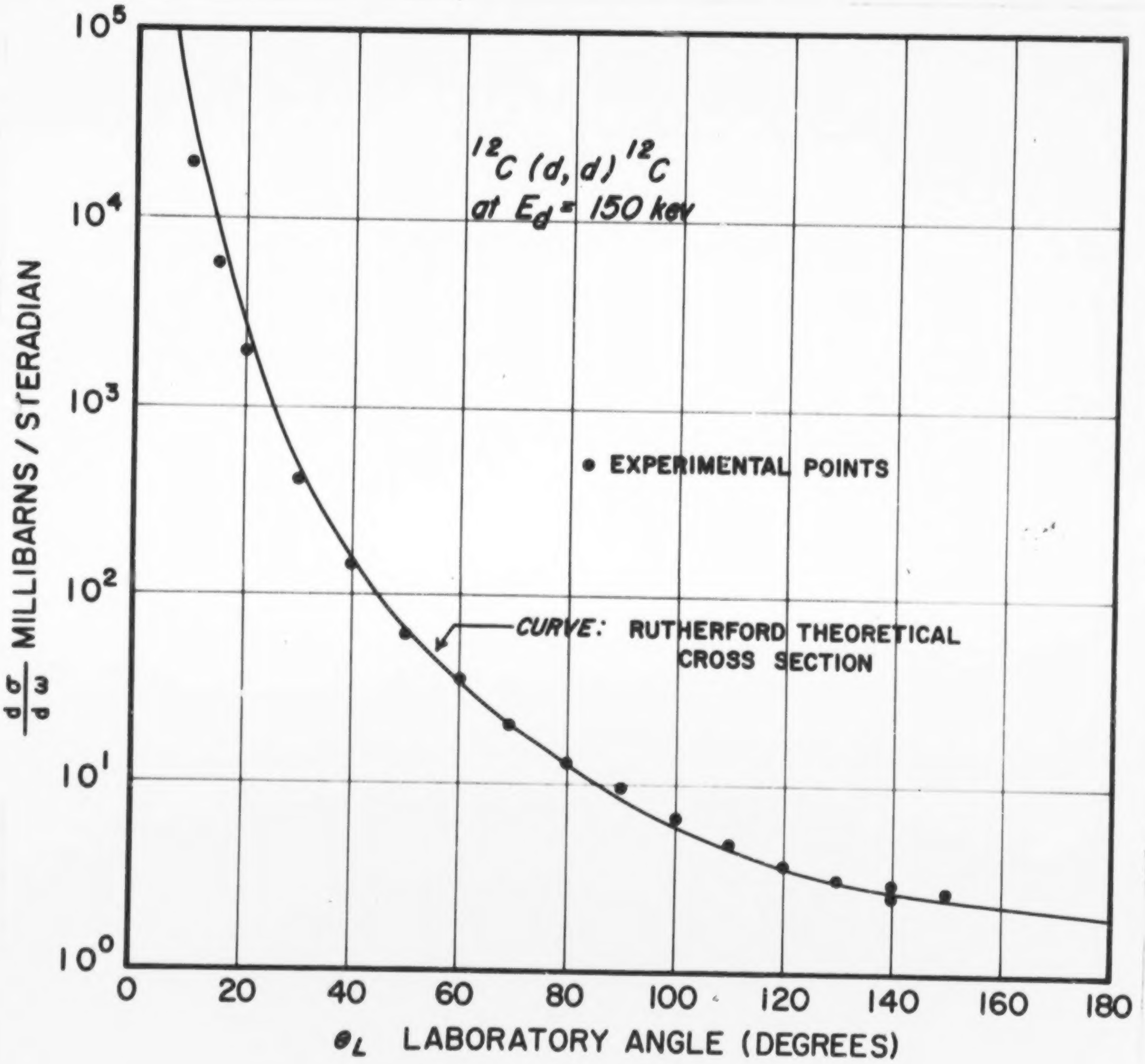

FIGURE 15. Angular distribution for the $^{12}C(d,d)\ ^{12}C$ Reaction at an incident Deuteron Energy of 150 keV.

measure the shape of the Rutherford Cross-section by using a monitor as shown in Figure 13. The shape of $\frac{d\sigma}{d\omega}$ is simply determined by taking the ratio of counts in the movable system to those in the monitor system.

Measurements similar to Figure 15 can be made for a variety of reactions. The format for the measurements is exactly as that described above. The author has successfully measured the Rutherford angular distributions at 150 KeV for targets of ^{12}C, ^{11}B, ^{58}Ni, and ^{197}Au when they were bombarded with protons, deuterons, and alphas. In addition to these the $^{12}C(^{3}He, {}^{3}He)^{12}C$ reaction has also been measured at 150 KeV and 300 KeV. The 300 KeV reaction was measured by using the doubly ionized ^{3}He beam from the accelerator. In a sense this is a method to double the effective voltage of an accelerator. Experience seems to indicate (Ref. 63) that .5% of the output of an RF type ion source is the doubly ionized component for either ^{3}He or alphas.

The complete Rutherford angular distribution as shown in Figure 15 can be measured in a four-hour laboratory period.

Neutron Time-of-Flight and Total Neutron Cross-Section Experiment

In this experiment, 14 MeV neutrons are produced by the $T(d,n)^4He$ reaction. The timing measurements are made by associated particle time-of-flight. Figure 16 shows a diagram of the essential features of the system. Neutrons from the reaction that leave in the forward direction (to the right in the figure) have an associated alpha particle that leaves in the opposite direction. In other words the angular separation between the neutron and the alpha is approximately 180°. These alpha particles are counted with a small solid state detector which is placed in the beam tube (at the bottom of the beam tube). Neutrons from the reaction are detected with a fast organic scintillator (NE 213 available from Nuclear Enterprises Ltd., Winnipeg, Canada). The phototube was a Phillips 56 AVP.

Figure 17 shows an electronic block diagram of the time-of-flight system. In the diagram, a pulse from the alpha detector is used to start the timing cycle of the time-to-pulse-height-converter (TPHC). The cycle is stopped with the corresponding neutron pulse from the phototube. The (TPHC) gives an output pulse whose magnitude is proportional to the difference in time (Δt) between the start and stop pulses. Additional information with regard to the time-of-flight method can be obtained in

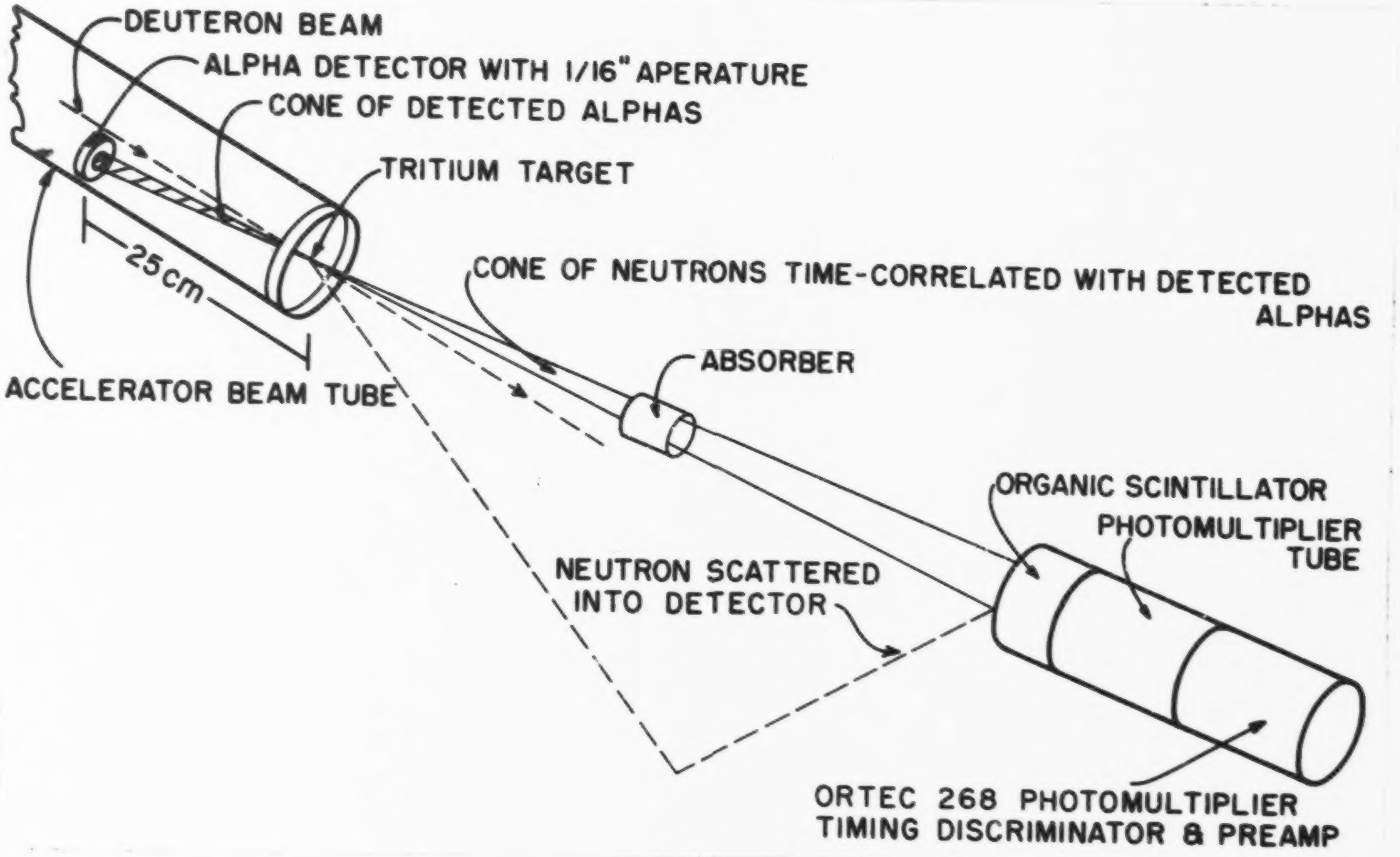
DEUTERON BEAM
ALPHA DETECTOR WITH 1/16" APERATURE
CONE OF DETECTED ALPHAS
TRITIUM TARGET
25cm
ACCELERATOR BEAM TUBE
CONE OF NEUTRONS TIME-CORRELATED WITH DETECTED ALPHAS
ABSORBER
ORGANIC SCINTILLATOR
PHOTOMULTIPLIER TUBE
NEUTRON SCATTERED INTO DETECTOR
ORTEC 268 PHOTOMULTIPLIER TIMING DISCRIMINATOR & PREAMP

FIGURE 16. System for Measuring Total Neutron Cross Section.

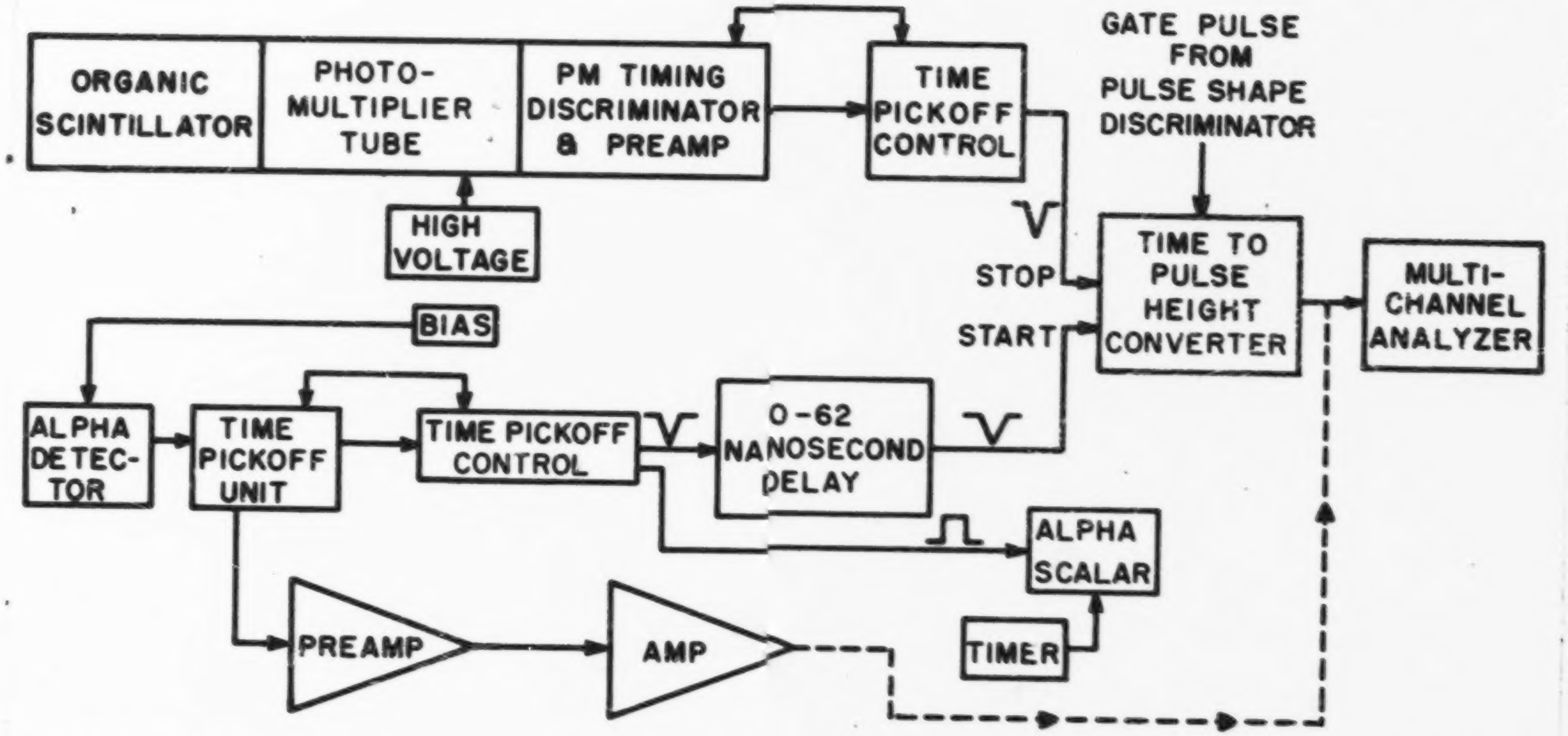
ORGANIC SCINTILLATOR
PHOTO-MULTIPLIER TUBE
PM TIMING DISCRIMINATOR & PREAMP
TIME PICKOFF CONTROL
HIGH VOLTAGE
GATE PULSE FROM PULSE SHAPE DISCRIMINATOR
STOP
START
TIME TO PULSE HEIGHT CONVERTER
MULTI-CHANNEL ANALYZER
BIAS
ALPHA DETEC-TOR
TIME PICKOFF UNIT
TIME PICKOFF CONTROL
0-62 NANOSECOND DELAY
ALPHA SCALAR
TIMER
PREAMP
AMP

FIGURE 17. Electronic Block Diagram for Total Cross Section Measurement.

References 64 and 65.

The output spectra of the (TPHC) can be seen in figure 18. In the figure the group which is marked 0.0 n sec corresponds to the output of the (TPHC) when there is Zero delay (ie. from the 0-62 nano-second delay box) in the start pulse circuit. The second group in the figure occurs when 10 n sec is introduced in the alpha circuit, etc. By changing these delays a time versus pulse height calibration can be made for the (TPHC). In the figure it can be seen that the slope of this curve is .257 n sec/ch. The time resolution of the system can be determined by multiplying the full width at half maximum (FWHM) for any of the groups times the slope of the time versus channel curve. For the groups in figure 18, the time resolution was 2 nano-seconds.

Figure 19 shows the pulse height spectrum that is observed if the alpha amplifier is fed into the analyzer. Shown also in the figure is a calibration curve and an ^{241}Am peak that was used for calibration.

Neutron-Flight-Time Measurements

For the measurements that will be described in this section Figure 16 (without the absorber) shows the experimental arrangement. Figure 20 shows a time spectrum that was measured with the neutron detector at a distance

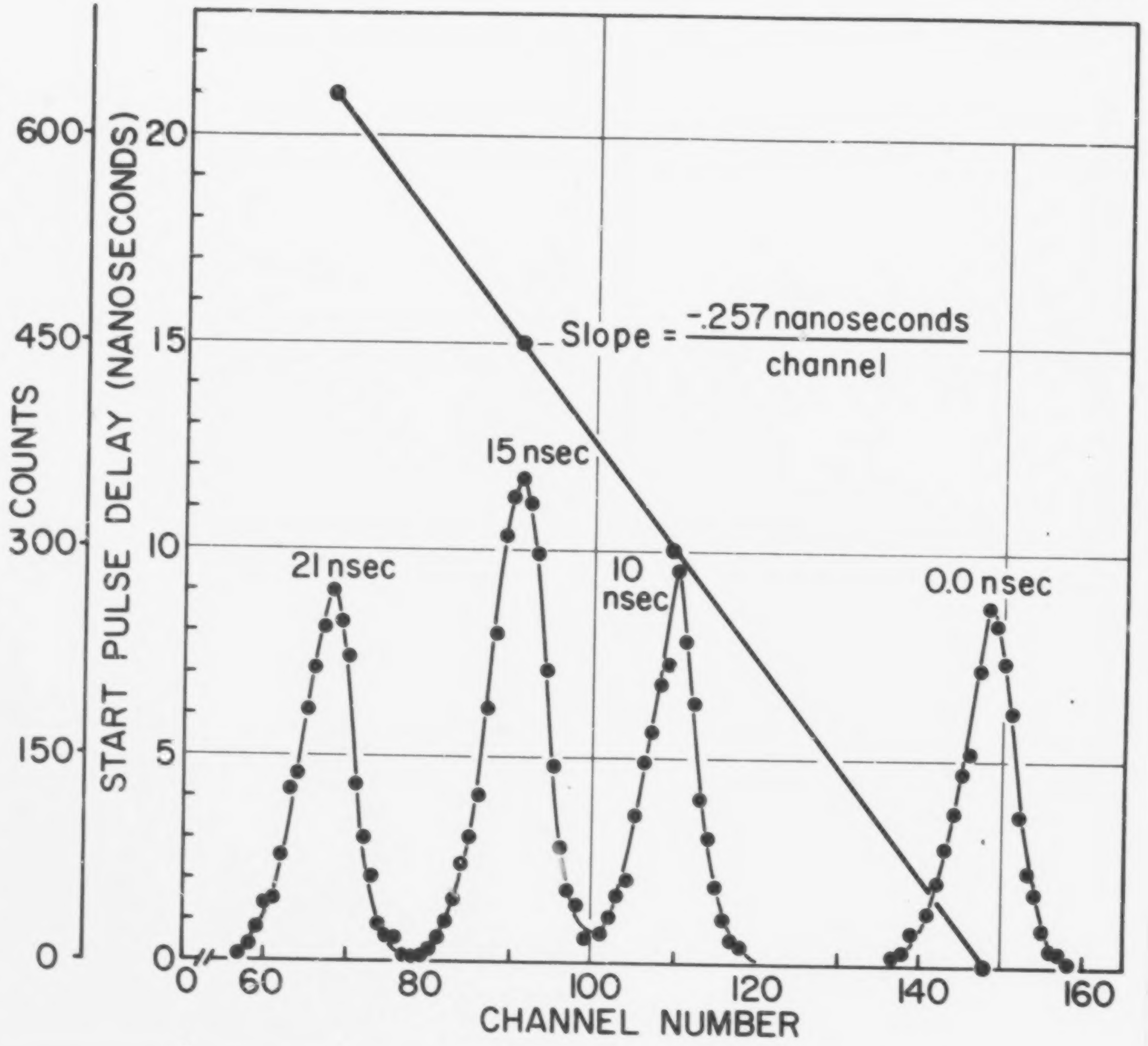

FIGURE 18. Time Calibration of Multichannel Analyzer.

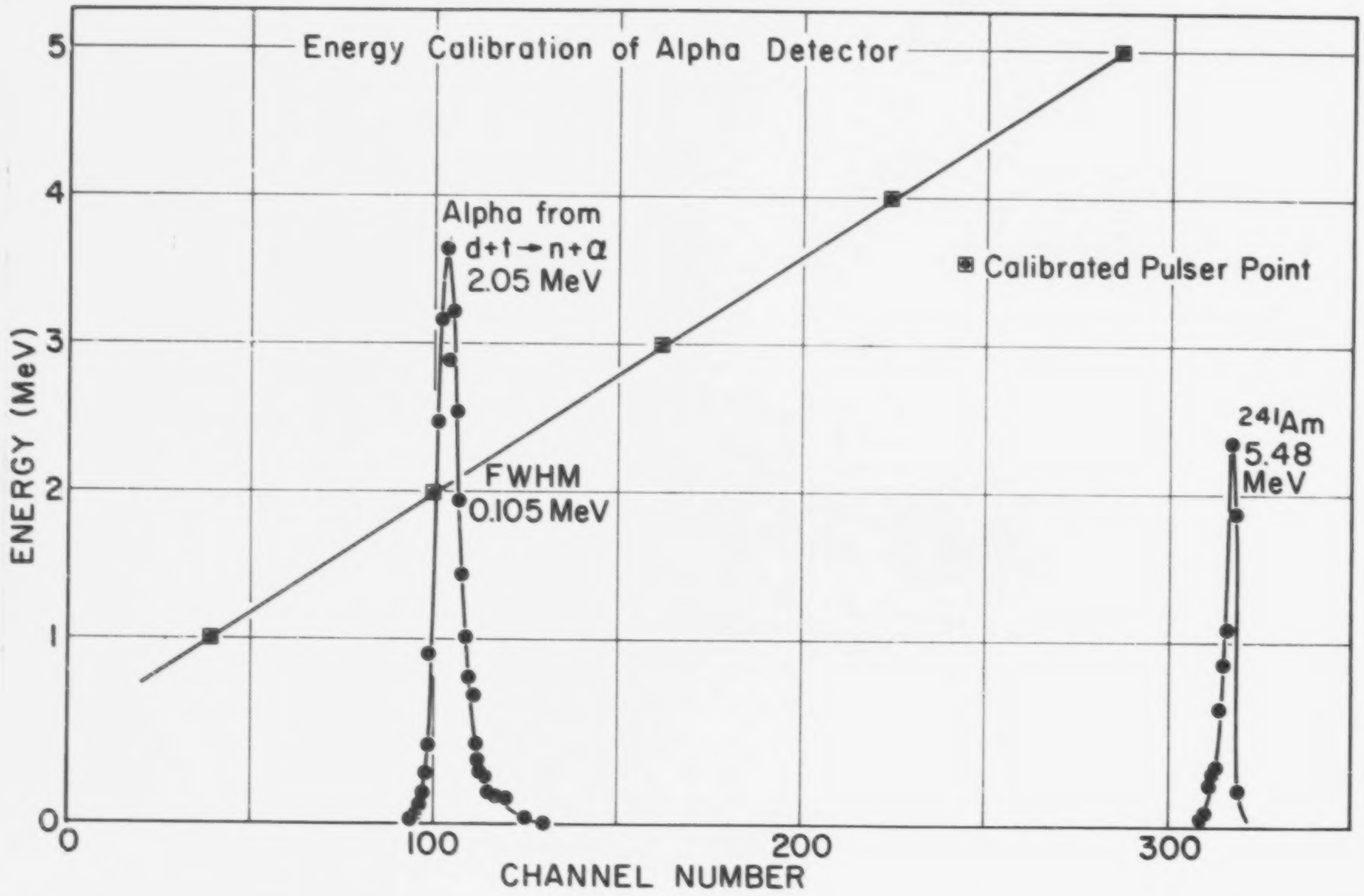

FIGURE 19. Determination of Associated Alpha Particle Energy.

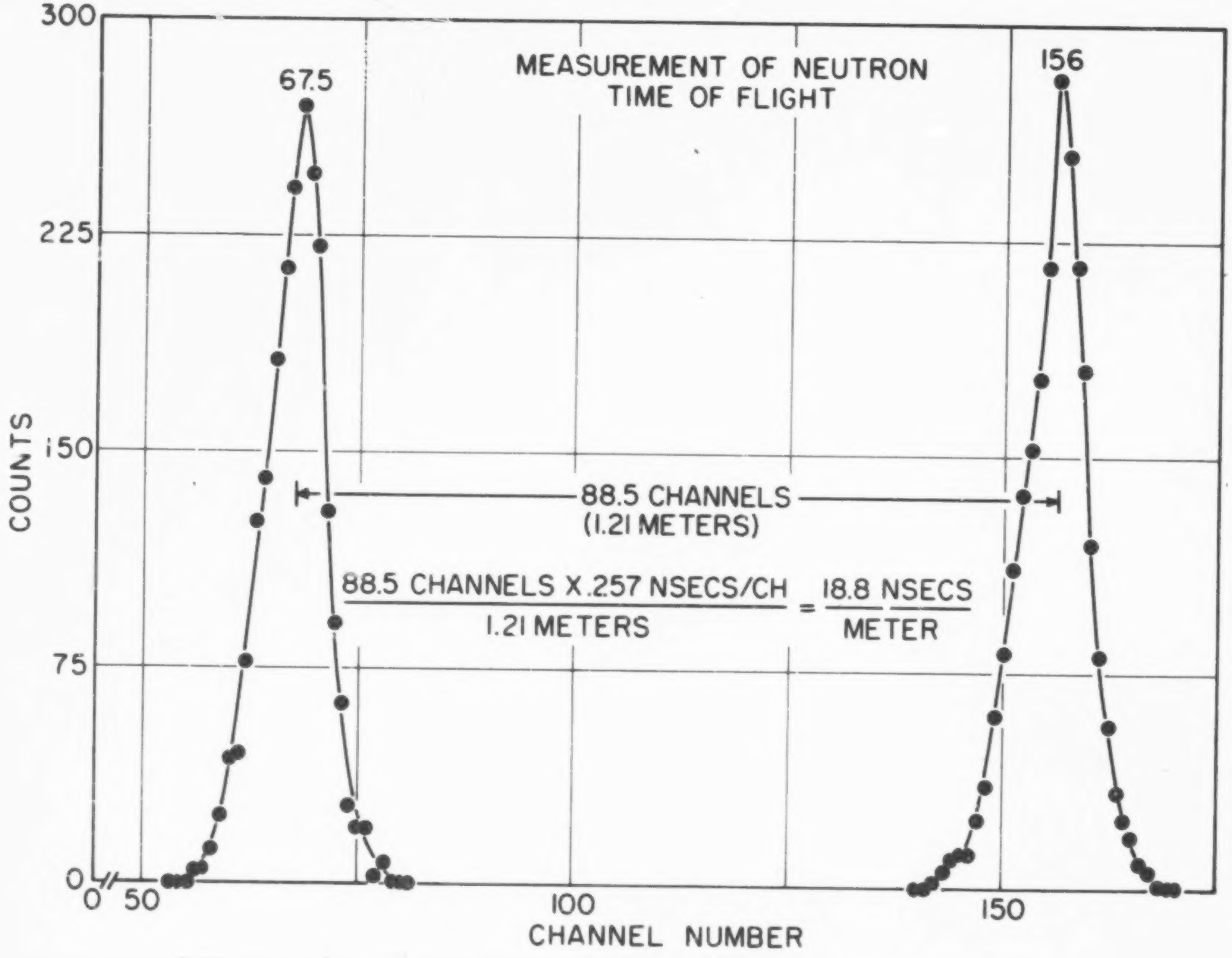

FIGURE 20. Neutron Velocity Determination.

L_o(~ .5 meters) from the target. The neutron group is shown at the left in the figure in channel 67.5. Next the neutron detector is moved 1.21 meters farther away from the target and the peak is observed to move to channel 156. From the calculation shown on figure 20 it can be seen that the experimental recriprocal velocity of the neutron group is 18.8 $\frac{\text{n sec}}{\text{meter}}$. The theoretical value for these 14.97 MeV neutrons is 18.6 n sec/meter.

Total Neutron Cross-Section

In figure 16, if N_o is the number of neutrons that are incident on the absorber and N is the number which pass through thickness (t) without an interaction. Then the following equations can be written:

$$N = N_o e^{-\mu t}$$

where μ in the above equation is the linear absorption coefficient. The total cross-section σ_t is given as:

$$\sigma_t = \frac{\mu}{n}$$

where n is the number of nuclei/cm^3 in the absorbing sample. These two equations can be combined to give:

$$\sigma_t = \frac{-\text{Ln } T}{nt},$$

where T is simply defined as $\frac{N}{N_o}$ (the transmission). Therefore the total cross-section can easily be determined by summing the number of counts from the TPHC (ie. one of the groups in Figure 20) with and without the absorber. Additional details on total cross-section measurements can be found elsewhere, References 66 and 67. Table III shows the measurements that were made in our laboratory for aluminum, Iron, Lead and Copper. The accepted values are taken from Reference 68. From Table

TABLE III

σ_T (barns)

Absorber	Measured	Accepted Value
Aluminum	1.75	1.7
Iron	2.48	2.5
Copper	2.85	2.9
Lead	5.11	5.6

III it is possible to determine the nuclear radius. The nuclear radius is related to the total cross-section in the following manner (see References 62 and 69):

$$\sigma_T = 2\pi(R+\lambdabar)^2$$

where R is the radius of the nucleus and $\lambdabar$ is the de Broglie wavelength of the neutron divided by 2π. It is also true that:

$$R = R_o A^{1/3},$$

where A is the particular nuclear mass number and R_o is the so-called unit nuclear radius. If $(\sigma_T)^{1/2}$ is plotted versus $A^{1/3}$ the slope of straight line should give the unit nuclear radius. When this was done for the measurements in Table III a value of 1.3×10^{-13} cm was obtained for R_o (see Figure 21). This value is in excellent agreement with the currently accepted value.

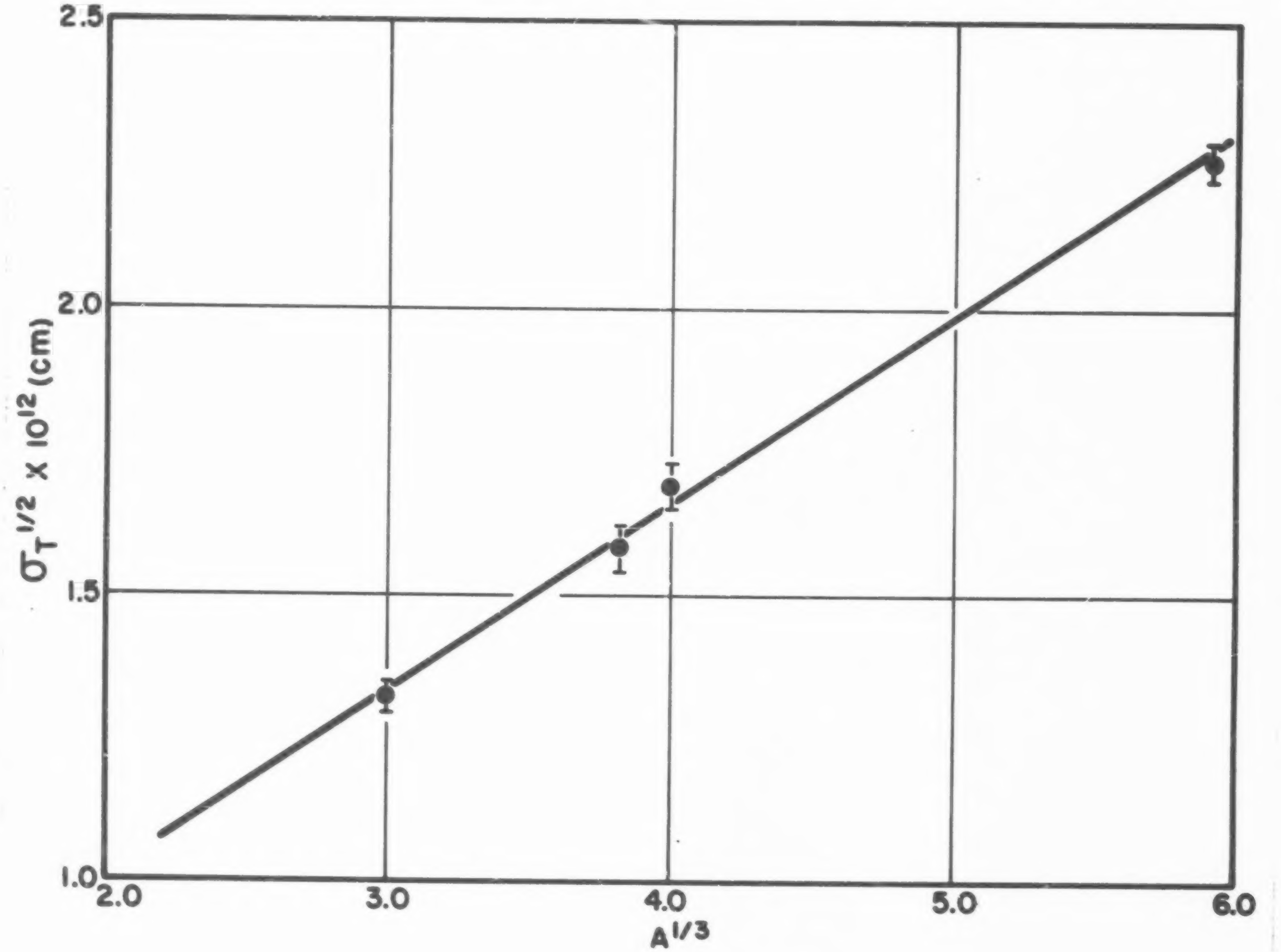

FIGURE 21. Nuclear Radius Determination.

Acknowledgments

The author would like to express his appreciation to Mr. E. H. Kobisk of the Isotope Production Center of the Oak Ridge National Laboratory for providing Table I (Appendix) and Ref. 3-11 on targetry. The data on the ^{6}Li + d reaction was taken in colaboration with Dr. L. S. Anthony, Physics Department, Roanoke College, Salem, Virginia. The data for the neutron-time-of-flight experiment was taken in colaboration with Dr. W. K. Robinson, Physics Department, St. Lawrence University, Canton, N. Y., and Mr. John Nagi, Hudson Valley Community College, Albany, N. Y. My co-workers for the rest of the experiments were Mr. John Yegge of the Oak Ridge Associated Universities and Mr. W. D. Adams of the Oak Ridge Operations office of the AEC. The author would like to give special thanks to all of these people.

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APPENDIX

A listing of the more ordinary samples available from the Oak Ridge National Laboratory Isotope Development Center, Oak Ridge, Tennessee is given. This outline assumes a target area of 6.5 cm^2, and the listed thickness limits are directly related to this target size. Sample thicknesses or target areas outside the noted ranges can usually be fabricated, but they are not considered routine samples and usually require discussions between the customer and Center personnel.

Target Preparations

Legend:
a -- evaporation
b -- rolling
c -- electrolytic deposition
d -- casting or pressing
f -- miscellaneous

1 -- self-supporting
2 -- metal backing
3 -- thin carbon

Element	Range of Thickness, µg/cm^2	Method of Preparation	Backing	Form of Deposit
Aluminum	5 to 12,000	a	2	Al
	150 up	a	1	Al
		d	1	Al
Americium	Undetermined	a		Am or Oxide
Antimony	500 to 3000	a	1	Sb
Arsenic	10 to 200	a	2	As
Barium	10 to 1000	a	2	Salt
		d	1	Salt
	2000 up	a,b	1,2	Ba
Beryllium	Undetermined	a	1,2,3	Be
Bismuth	500 to 15,000	a	1	Bi
	10 to Undetermined	a	2	Bi
Boron	20 to 250	a	1	B
	10 to 1000	a	2	B
Bromine	10 to 1000	a	2	Bromide
	500 up	d	1	Bromide
Cadmium	10 to 200	a	2	Cd
	1000 up	b	1	Cd
		d	1	Cd

Element	Range of Thickness, μg/cm^2	Method of Preparation	Backing	Form of Deposit
Calcium	10 to 1000	a	2	Ca
	700 up	b	1	Ca
		d	1	Ca or Carbonate
Californium	100	c	2	Oxide
Carbon				
Normal	1.5 to 200	a	1	C
Isotopic	10 to 200	f	2	C
Cerium	10 to Undeter=mined	a	2	Ce Oxide
Cesium	10 to 1000	a	2	Salt
Chlorine	10 to 1000	a	2	Salt
	5000 up	d	1	Salt
Chromium	500 to 12,000	a	1	Cr
	10 to Undetermined	a	2	Cr
		d	1	Cr
Cobalt	1000 up	b	1	Co
	10 up	a	2	Co
	100 to 1000	a	1	Co

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Copper	500 up	b	1	Cu
	10 to 1000	c	2	Cu
	200 up	a	1	Cu
		d	1	Cu
Curium	10 up	a	2,3	Oxide
Dysprosium	2000 to 25,000	b	1	Dy
	10 up	a	2	Dy
Drbium	10 to Undetermined	a	2	Er
	2000 up	b	1	Er
Europium	10 to Undetermined	a	2	Eu
	1000 up	b	1	Eu
Fluorine	25 to 500	a	2	Fluoride
Gadolinium	2000 to 25,000	b	1	Gd
	10 up	a	2	Gd
Gallium	10 to Undetermined	a	2	Ga
	10 to 200	a	3	Ga_2O_3
		d	1	Ga_2O_3

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Germanium	10 up	a	2	Ge
	300 to Undetermined	a	1	Ge
Gold	10 up	a	2	Au
	Undetermined	a	1	Au
		d	1	Au
^3H Adsorbed on Zr, Y, Ti, or Er	100 to 5000	f	2	Metal
Indium	5000 up	b	1	In
	10 up	a	2	In
		d	1	In
Iridium	10 to 100	a	2	Ir
Iron	500 up	b	1	Fe
	10 up	a	2	Fe
		d	1	Fe
Lanthanum	10 to Undetermined	a	2	La
	2000 up	b	1	La
		d	1	La

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Lead	8000 up	b	1	Pb
	500 to 8000	a	1	Pb
	10 to 1000	a	2	Pb
		d		Pb
Lithium	4000 to any cast size	b,d	1	Li
	10 to 500	a	3	LiH
	10 to 500	a	2	Li
Luthetium	10 to Undetermined	a	2	Lu
Magnesium	150 to 1000	b	1	Mg
	up to 20,000	a	1	Mg
		d	1	Mg
Manganese	300 to 1600	a	1	Mn
	10 to Undetermined	a	2	Mn
Mercury	1000 to 4000	c	on Au	Hg
	Undetermined	a	2	Salt
Molybdenum	10 to 1000	a	2	Mo
	1000 up	b	1	Mo

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Neodymium	10 to Undetermined	a	2	Nd
	1000 to 15,000	b	1	Nd
Neptunium	10 up	a	2,3	Oxide
Nickel	500 up	b	1	Ni
	10 up	a	2	Ni
		d	1	Ni
Niobium	10 up	a	2	Nb
	1000 up	b	1	Nb
Palladium	1000 up	b	1	Pd
	10 up	a	2	Pd
		s	1	Pd
Platinum	4000 up	b	1	Pt
	10 up	a	2	Pt
		d	1	Pt
Plutonium	10 up	a	2	Oxide
	5000 up	b	1	Pu(1% Al)
Potassium	7500 to any cast size	b,d	1	K

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Promethium	10 up	a	2	Pm Oxide
		a	2	Pm
Radium	10 up	a	2	Bromide
Samarium	1000 to Undetermined	b	1	Sm
	10 up	a	2	Sm
Scandium	10 up	a	2	Sc
	1000 up	b	1	Sc
Selenium	300 to 5000	a	1	Se
	10 to 5000	a	2	Se
		d	1	Se
Silver	1000 up	b	1	Ag
	100 to 5000	a	2	Ag
	10 to 1000	a	2	Ag
		d	1	Ag
Silicon	10 to 1000	a	2	Si
	50 to 400	a	1	Si
	10 to 150	a	2,5	SiO_2
Sodium	7500 to any cast size	b,d	1	Na
Strontium	2000 up	b	1	Sr

Element	Range of Thickness, μg/cm^2	Method of Preparation	Backing	Form of Deposit
Sulfur	5000 up	d	1	S
	10 to 100	a	2	S
Tantalum	1000 up	b	1	Ta
	10 to 1000	a	2	Ta
Technetium	10 to 1000	a	2	Tc
Tellurium	10 to 1000	a	2,3	Te
		d	1	Te
Thallium	8000 up	b	1	Tl
	10 up	a	2	Tl
Thorium	4000 up	b	1	Th
	10 up	a	3	Th
Tin	4000 up	b	1	Sn
	10 to 1000	a	2	Sn
	500 to 4000	a	2	Sn
Titanium	500 up	b	1	Ti
	10 up	a	2	Ti
Tungsten	In Cu Matrix	b	2	W
	>2000	d	1	W
Uranium	10 up	A	2	Oxide
	5000 up	b	1	U
Vanadium	1000 up	b	1	V
	10 up	a	2	V

Element	Range of Thickness, $\mu g/cm^2$	Method of Preparation	Backing	Form of Deposit
Ytterbium	10 to Undetermined	a	2	Yb
	1000 up	b	1	Yb
Yttrium	10 to Undetermined	a	2	Y
	700 up	b	1	Y
Zinc	1000 up	b	1	Zn
	10 up	a	2	Zn
Zirconium	500 up	b	1	Zr
	10 to 5000	a	2	Zr

A Van de Graaff Nuclear Physics Laboratory Using a 500 keV Accelerator

Presented by William Bygrave
High Voltage Engineering Corp.
Burlington, Massachusetts

at the ANS Small Accelerator Symposium
New York, New York - April 1969

INTRODUCTION

During the past 20 years, much of our knowledge of the nucleus has come from research with accelerators. But, although many universities throughout the world have accelerators on campus and others have access to experimental facilities at national and international accelerator laboratories, nuclear physics at final-year undergraduate and first-year graduate level is taught with courses which generally do not include even the simplest of nuclear reactions. Indeed, a student is very fortunate if he gets to measure a Rutherford scattering cross-section with apparatus which was frontier fifty years ago.

In an attempt to remedy this, we have designed a laboratory course[1] for a 500 keV accelerator which allows the student to get to the very heart of the nucleus and so gain a much greater insight into its constituents and properties. Experiments such as pulse circuitry, detector calibration, interaction of radiations with matter, and radioactive decay, which previously have formed a complete nuclear physics course, are used as stepping stones towards the understanding of the nucleus through nuclear reactions.

All of the experiments which are fundamental to the basic course have been tried on a similar package at Georgetown University, Washington, D. C. by Drs. P. Treado and J. Lambert.[2] High Voltage Engineering is publishing a Handbook of Nuclear Physics Experiments which enables both the instructor and the student to perform the course without any previous intensive training in nuclear physics.

Table I presents a list of the experiments and relates them to the physics principles and the experimental techniques which the student should understand when he has completed the course. There are enough experiments in the basic course to last a full year with four hours of laboratory work per week, but it is sufficiently flexible that a meaningful course can be designed for a one semester, four hours per week class.

The first experiments acquaint the student with the latest accelerator designs from the ion source through to the analysis magnet. After this he becomes familiar with detection methods which include not only the older types of detectors such as ionization and scintillation, but also surface barrier types.

The next experiments use the accelerator to explore the nucleus. The student starts with Rutherford scattering so he gets a feel for two of the fundamental nuclear properties: charge and size. At this point he is introduced to the concept of cross-section and measures it. After this he investigates a nuclear reaction in which he measures the energy release, 'Q' value, and verifies the kinematics;

TABLE 1

30 EXPERIMENTS

		BASIC COURSE																			OPTIONAL I								OPTIONAL II		
		ACCELERATOR SYSTEM OBSERVATION	ACCELERATOR SYSTEM OBSERVATION	DETECTOR ELECTRONICS	ACCELERATOR ENERGY CALIBRATION	IONIZATION CHAMBER DETECTORS	SCINTILLATION CRYSTAL DETECTORS	SURFACE BARRIER DETECTORS	RUTHERFORD SCATTERING	Q-VALUE $Li^6(p, He^3)He^4$	Q-VALUE $P^{31}(p,\gamma)S^{32}$	REACTION KINEMATICS	NEUTRON DETECTION	$H^2(d,p)H^3$ REACTION	WATER MODERATOR	γ-γ COINCIDENCES	β-γ COINCIDENCES	INELASTIC NEUTRON SCATTERING	He^4-He^3 COINCIDENCES	$Li^6(d,p)Li^7$, $Li^6(d,\alpha)He^4$	COPPER (n, 2n)	FERMI AGE OF NEUTRONS	$C^{12}(p,p)$	Ni (d,d)	NEUTRON-PROTON MASS DIFFERENCE	SHORT HALF LIVES	NEUTRON CAPTURE γ RAYS	$P^{31}(p,\gamma)S^{32}$ ANGULAR DISTRIBUTION	$Li^7(p,p)Li^7$	$C^{12}(p,p)C^{12}$	$Li^7(p,\gamma)Be^8(2)He^4$
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	01	02	03	04	05	06	07	08	001	002	003
THE NUCLEUS	CHARGE		●		●				●	●	●	●		●					●	●			●	●					●	●	●
	MASS		●		●				●	●	●	●		●					●	●			●	●					●	●	●
	SIZE								●														●	●					●	●	
	ANGULAR MOMENTUM																											●	●		
	PHOTONS AND NEUTRONS								●				●	●																	
RADIATIONS	β^+					●	●								●											●					
	β^-						●														●										
	γ				●		●				●					●	●									●	●				●
	He^4 (α)							●		●		●							●	●											●
	n						●						●		●			●			●	●			●	●	●				
TYPES OF REACTION	ELASTIC SCATTERING								●														●	●					●	●	
	INELASTIC SCATTERING																	●													
	SIMPLE CAPTURE										●					●											●	●			
	DISINTEGRATION									●		●	●	●	●		●		●	●	●	●			●	●	●				●
	SPONTANEOUS DECAY					●	●	●							●						●	●				●					
CONSERVATION LAWS	ENERGY											●	●						●	●											
	MOMENTUM											●	●						●	●											
	CHARGE											●	●						●	●											
	NUCLEONS											●	●						●	●											
	ANGULAR MOMENTUM																											●	●		
REACTION PARAMETERS	CROSS SECTION								●														●	●				●	●		
	EXCITATION FUNCTION				●												●												●		
MASS AND ENERGY	EQUIVALENCE OF MASS AND ENERGY									●	●	●							●						●						
	CREATION AND ANNIHILATION						●									●					●										
QUANTUM, WAVE MECHANICS	ENERGY LEVELS						●				●					●											●	●			
	BARRIER PENETRATION									●	●	●				●	●			●								●			●
INTERACTION OF RADIATION AND MATTER	PHOTO ELECTRIC EFFECT						●																								
	COMPTON EFFECT						●																								
	PAIR PRODUCTION						●																								
	IONIZATION					●		●																							
NUCLEAR LIFETIMES	HALF-LIFE					●									●						●					●					
NEUTRONS	CAPTURE																										●				
	MODERATION														●							●									
ELECTROSTATICS	VAN DE GRAAFF PRINCIPLE	●	●																												
	ELECTROSTATIC VOLTMETER		●																												
CHARGED PARTICLE DYNAMICS	ACCELERATION	●	●		●																										
	MOTION IN A MAGNETIC FIELD	●	●		●																										
DETECTORS	IONIZATION					●									●							●									
	SCINTILLATION						●				●		●		●	●	●	●			●	●				●	●				
	SOLID STATE							●	●	●		●		●			●		●	●			●	●	●			●	●	●	●
ELECTRONICS	BASIC PULSE CIRCUITRY			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
VACUUM	BACKING PUMP	●	●																												
	DIFFUSION PUMP	●	●																												
	MEASUREMENT OF PRESSURE	●	●																												
HEALTH PHYSICS	RADIATION SURVEY		●		●							●																			

this demonstrates the equivalence of energy and mass and the penetration of a potential barrier, which is predicted by wave mechanics. He becomes familiar with γ-rays from various nuclear reactions such as $P^{31}(p,\gamma)S^{32}$. Neutrons are produced with the accelerator and detected with a stilbene crystal. The neutrons come from the $H^2(d,n)He^3$ reaction and the next experiment detects the protons from the $H^2(d,p)H^3$ reaction, so the student has an insight into the fact that protons and neutrons are the basic building blocks of the nucleus.

Two experiments which use neutrons from the $H^2(d,n)He^3$ reaction are included: in the first, the neutron flux distribution in a water moderator is measured, and in the second, neutrons are inelastically scattered from iron.

The student is acquainted with coincidences by observing γ - γ events from the $P^{31}(p,\gamma)S^{32}$ reaction and α-γ events from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction.

Many other physical processes and experimental techniques are learned during the course, including the following: interaction of photons with matter (photoelectric effect, Compton scattering, and pair production); creation of electron-positive ion pairs; resonances in reaction cross-sections; the concept of half life; radiation monitoring for Health Physics; vacuum technology; and neutron activation.

For the basic set of experiments we deliberately have avoided the use of radioactive sources (such as Am^{241}) and targets (such as Tritium) for which the laboratory must have an AEC license. However, we realize that many schools already hold these and others are ready to obtain them, so we have included experiments with a tritium target in the optional set No. I. Also in this group we have put experiments which we consider more advanced, and so more difficult, than the basic set. A second optional set -- No. II -- contains experiments which are as simple as the basic set but require an energy somewhat above 400 keV. These experiments should only be performed by a skilled student who has become completely familiar with the Van de Graaff.

Wherever it is appropriate, the handbook outlines the history and philosophy leading to and following an important discovery, and in some cases, we have selected the same reaction which the original discoverer used -- who could fail to be excited when he repeats Cockcroft and Walton's experiment? The student is referred to the original publication on the classic experiments of nuclear physics.

Table (1) is an impressive list which illustrates the following excerpt from the National Science Foundation publication NSF-62-45 "Research Trends, 1962-1967, Nuclear Structure Physics":[4]

> "Any discussion of science education necessarily involves the consideration of scientific research. Few fields surpass nuclear structure research as a training ground for young scientists. It is an important subject characterized by exciting activity. The concepts involved center on modern physics and range over a vast

> domain involving solid-state physics on the one hand, and elementary-particle physics on the other. The experimental techniques involve a similarly broad domain.
>
> The breadth and utility of training in this field are attested by the versatility of its graduates. Every major field in the physical sciences has been strengthened by the acquisition of young scientists who received their training in nuclear physics, and technology has similarly benefited. Currently more than a quarter of the physics doctoral theses pertain to nuclear structure physics.
>
> Unfortunately, in some post-graduate research the apparatus is so expensive that the student is relegated to the role of assistant to the more experienced research personnel. Such research projects, often characterized by team efforts and time schedules, fall short of the ideal for training the young scientist. In nuclear structure research, however, the student is frequently made responsible for the entire research project -- a responsibility which often includes the conception of the project itself. The environment fosters his development as an independent thinker capable of choosing his own problems and developing them to their logical limits."

EXPERIMENTAL EQUIPMENT

The experimental equipment was selected using these criteria: it should be reliable and easy to operate, it could be used for both teaching and research, it should be expandable, it should be inexpensive, and it should make a complete laboratory.

Figure 1 shows in schematic form the apparatus which we have included in our basic package.

The accelerator is a model AN-500, 500 keV Van de Graaff accelerator which is connected to a magnet which can be used to analyze and switch the beam into three different target positions:

NUCLEAR PHYSICS TEACHING SYSTEM

APPARATUS AND ACCESSORIES

SCATTERING CHAMBER AND TARGETS

SCAT - Scattering Chamber
  Targets[+]
    Gold
    Nickel
    Carbon
    Phosphorus
    Fluorine
    Deuterium - Thin
    Lithium

DETECTORS

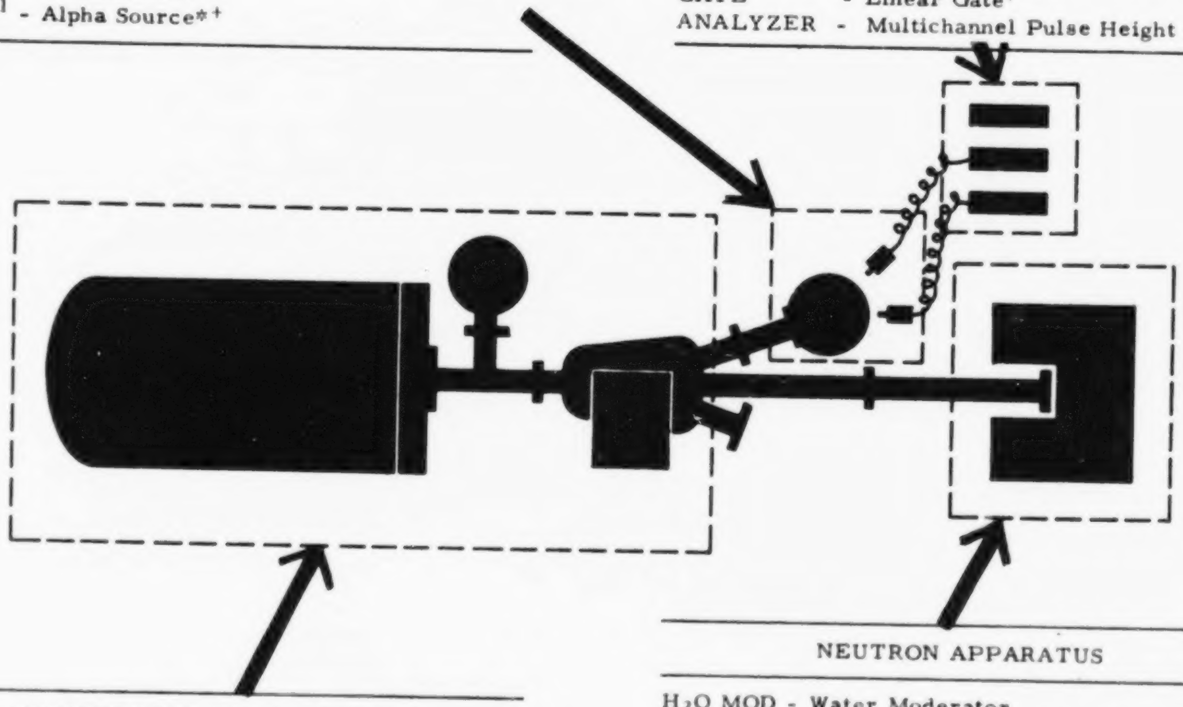
NAI - NaI Detector (2)
STIL - Stilbene Crystal
Au-Si - Au-Si Detector (2)
GC - Geiger Counter

RADIOACTIVE SOURCES

Po^{210} - Alpha Source
Cs^{137} - Gamma Source
Na^{22} - Gamma Source
Co^{60} - Gamma Source
Am^{241} - Alpha Source[*][+]

ELECTRONICS

BIN - Bin and Power Supply
RCAMP - RC Amplifier (2)
SCA - Single Channel Analyzer (2)
COIN - Coincidence Analyzer
PULSER - Pulser
SCALER - Scaler
TIMER - Timer
PREAMP (SCINT) - Scintillation Preamplifier (2)
PREAMP (Au-Si) - Semiconductor Preamplifier (2)
DELAY - Linear Delay
BIAS - High Voltage Power-Supply
GC - Scaler, Power Supply for Geiger Counter
CINT - Current Integrator
GSM - Radiation Survey Meter
FNS - Fast Neutron Survey Probe[+]
BIN - Bin and Power Supply[+]
DISC - Discriminator [+]
DDLAMP - Double Delay Line Amplifier [+] (2)
SCALER - Scaler[+]
GATE - Linear Gate[+]
ANALYZER - Multichannel Pulse Height Analyzer



ACCELERATOR AND ACCESSORIES

VDG - 500 keV Van de Graaff Accelerator
MAG - Switching-Analyzing Magnet and Power Supply
IBTS - Ion Beam Transport System

NEUTRON APPARATUS

H_2O MOD - Water Moderator
HOLDER - Deuteron Target Holder
DEUT - Deuterium Target
In FOIL - Indium Foils
Cd FOIL - Cadmium Covers
Cu FOIL - Copper Foil[+]
TRIT - Tritium Target[*][+]

[+] Optional Equipment
[*] AEC License Required

Figure 1.

one with a scattering chamber, one for a neutron target and water moderator, and one which can be used as a beam line for research.

The electronics is modular AEC-type. We selected the Canberra 800 EDUCATOR[5] series which is an inexpensive line of equipment based on the Canberra 1400 Research Series. However, if a university wants to use the accelerator for an extensive research program, then it might be wise to substitute better equipment right at the start, e.g. Canberra 1400 or Ortec.[6] The high voltage power supply is the Ortec design with four individually adjustable 0 - 1000 volt bias outputs so this can be used simultaneously for four detectors. The Geiger counter comes in a complete unit with a power supply and scaler so that it can be used independently of the other electronics. A general purpose radiation survey meter is supplied with a probe for alpha, beta, and gamma detection and this can be equipped with a fast neutron probe. The current integrator has a current range of 3×10^{-9} amps to 1×10^{-3} amps. Any multichannel pulse height analyzer can be used with this system and the choice would probably be determined by the research applications of the user. If teaching is the only interest, then all that is needed is a 128 channel analyzer. The optional equipment is only needed for some of the more elaborate experiments which are included in the optional set of experiments. While it is not essential, it can be used to improve the experimental techniques in the basic set.

The detectors include two 2" x 2" NaI (Tℓ) assemblies, one 2" diameter x 1/2" thick stilbene crystal, interchangeable with the

NaI (Tl) crystal supplied with the scinitillation detector, two Au-Si detectors 50 mm^2 with a depletion depth of 60 μ, and a Geiger counter with a 2-3 mg/cm^2 end window.

No AEC license is required with the basic set of radioactive sources. The γ-ray sources have activities in the region of 1 microcurie and the α -source an activity of $10^3 - 10^4$/minute. If the school holds an AEC license, then it should use the Am^{241} source because it has a much longer half-life than Po^{210}.

The neutron apparatus includes a water moderator, a target holder, a 2.5 mg/cm^2 deuterium target, indium foils 0.25 mm thick, cadmium foils 0.51 mm thick, and a copper foil 0.25 mm thick. If the school has the necessary AEC license and adequate neutron shielding around the accelerator, it may want to use a tritium target, 2.5 mg/cm^2 thick.

Of course, the AEC standards for radioactive materials do not apply to countries outside the U.S.A., so other regulations and codes of practice will have to be observed.

Our choice of experiments for this course has been influenced by the availability or ease of fabrication of certain targets. The gold target is the thinnest gold leaf which is commercially available and is approximately 5 x 10^{-5} cm thick. Likewise, the nickel target is commercial leaf 5 x 10^{-5} cm thick. This is not the ideal for nuclear physics experiments, but it is more than adequate for Rutherford scattering with 400 keV protons and it has the virtue of being cheap and easy to handle in comparison with evaporated targets. The carbon film is approximately 40 $\mu g/cm^2$ thick and is available from Oak Ridge National Laboratory, U. S. A., and Yssom University, Israel. It comes evaporated on a glass slide and has to be floated off with the standard techniques. The zinc phosphide is an evaporated layer on a solid backing. The fluorine target is made by etching a solid backing such as copper or nickel with hydrofluoric acid vapor and can be made either thick or thin. Thin deuteron targets are commercially available as a layer of deuterated titanium 350 $\mu g/cm^2$ thick on a copper backing. The lithium target is fabricated by evaporating natural lithium on to a thin backing film such as carbon.

Figures 2A and 2B show the AN-500 Van de Graaff and its specifications. It has a maximum voltage of 500 kV with a maximum beam current of 150 μA. For the teaching package the accelerator is fitted with hydrogen and deuterium gas bottles, since the course only requires deuteron and proton beams. For research applications, this same basic machine can be extended by the addition of other gas bottles such as He^3 and He4, by the addition of a microsecond positive ion pulser, and by conversion to electron operation.

The analyzing and switching magnet is shown in Figures 3A and 3B. It has three output ports at ± 15° and 0° and suitable power supplies are available to give either $\frac{M \times E}{Z^2} = 0.8$ or $\frac{M \times E}{Z^2} = 4$

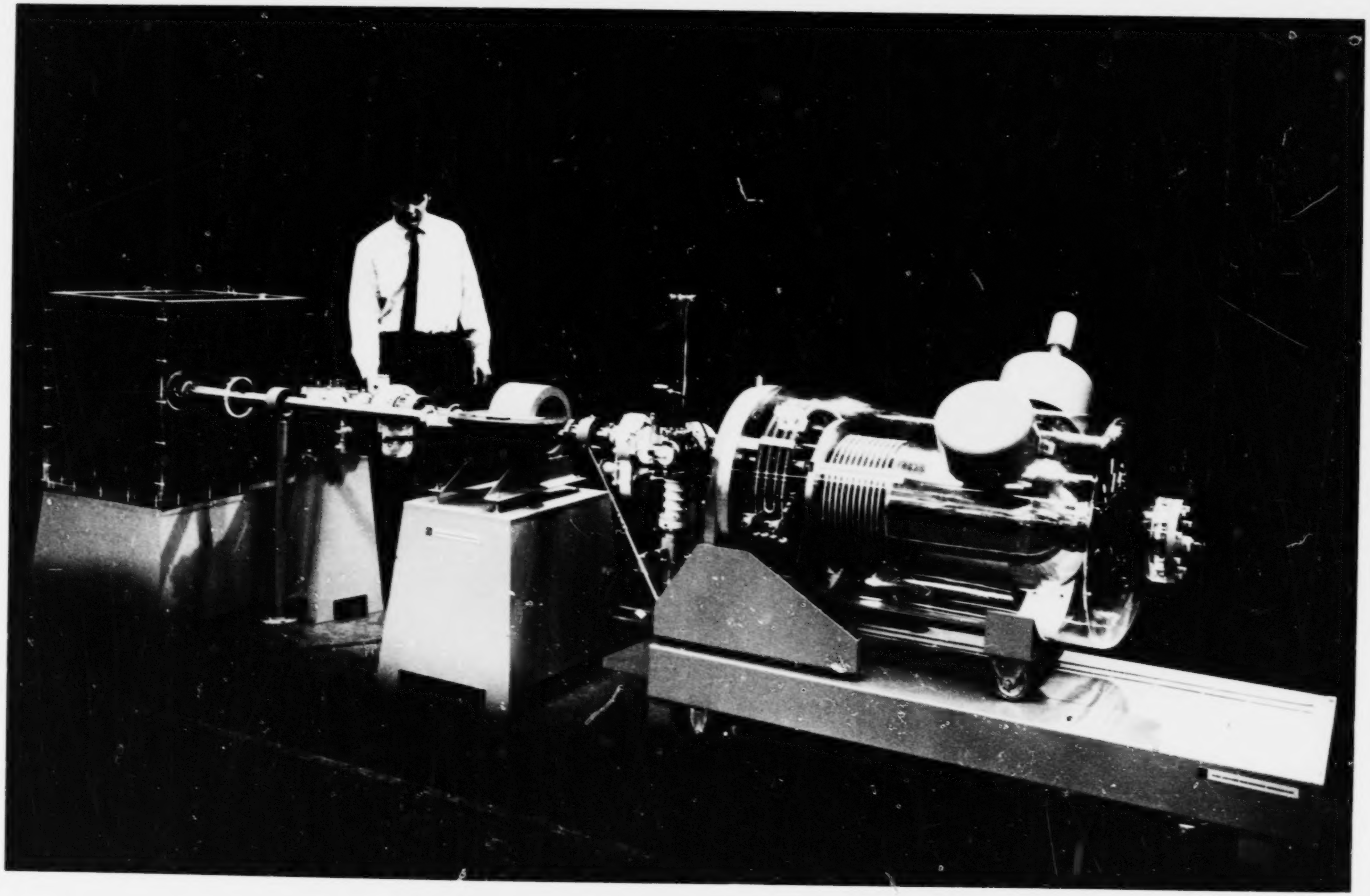


Figure 2a. 500 keV Van de Graaff, with analyzing/switching magnet, scattering chamber, and moderator

The Five Hundred Kilovolt Van de Graaff Accelerator

AN-500 Ion Beam Operation

Acceleration Voltage (continuously adjustable)	200 – 500 kilovolts
Beam Current (d.c.) (continuously adjustable)	10 – 150 μA
Beam Diameter at Standard Target Distance	1 cm for 90% of beam current

Positive ion pulsing is available as an optional extra.

Pulsed Beam Current Amplitude	10 – 100 μA adjustable
Duty Cycle	10% maximum
Pulse Duration	10 – 200 microseconds*
Pulse Repetition Rate	1 – 10,000 pulses/second*
Pulse Rise and Decay Time (measured at 3 dB points)	3 microseconds maximum
Neutron Output (D-t Reaction)	Better than 2×10^{10} n/s

*Pulse duration and pulse repetition rate are selected by an external switch with 12 positions. Six of the positions are factory wired with standard combinations of pulse duration and repetition rate. The six extra switch positions are available for additional pulsing arrangements.

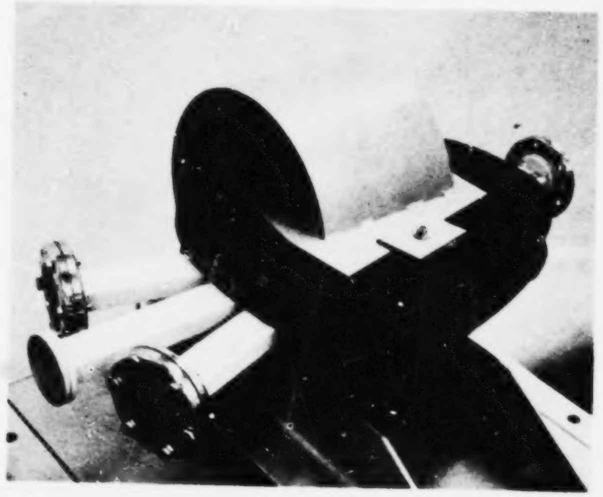
Factory Wired:	Pulse Duration ± 10%	Pulse Repetition Rate ± 10%
	10 microseconds	10,000 pulses per second
	50 microseconds	1,000 pulses per second
	150 microseconds	500 pulses per second
	200 microseconds	100 pulses per second
	200 microseconds	10 pulses per second
	200 microseconds	1 pulse per second

Electron operation is available as an optional extra.

AS-500 Electron Operation

	Standard	Stabilized
Beam Energy	200 – 500 keV	100 – 500 keV
Beam Current		
Minimum	1 μA	1 μA
Maximum	100 μA	100 μA
Beam Current Stability	—	±5% or 0.5 μA whichever is greater
Beam Diameter for 90% of beam current at standard target distance	1 cm	1 cm
Voltage Stability at Terminal		±5 kV
X-ray Output	> 100 r/hr	> 100 r/hr

Figure 2b. The five hundred kilovolt Van de Graaff Accelerator



Power Supply 40V 2A, Field Max. 1,250 gauss,

ρ = 40'' (102 cm), $\frac{M \times E}{Z^2} = 0.8$

Power Supply 80V 5A, Field Max. 2,900 gauss,

ρ = 40'' (102 cm), $\frac{M \times E}{Z^2} = 4.0$

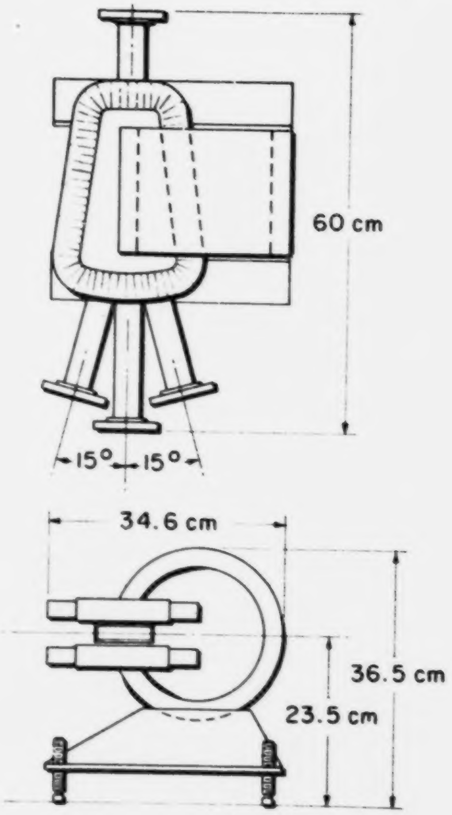

60 cm
15°
15°
34.6 cm
36.5 cm
23.5 cm

Figure 3a. Analyzing/switching magnet

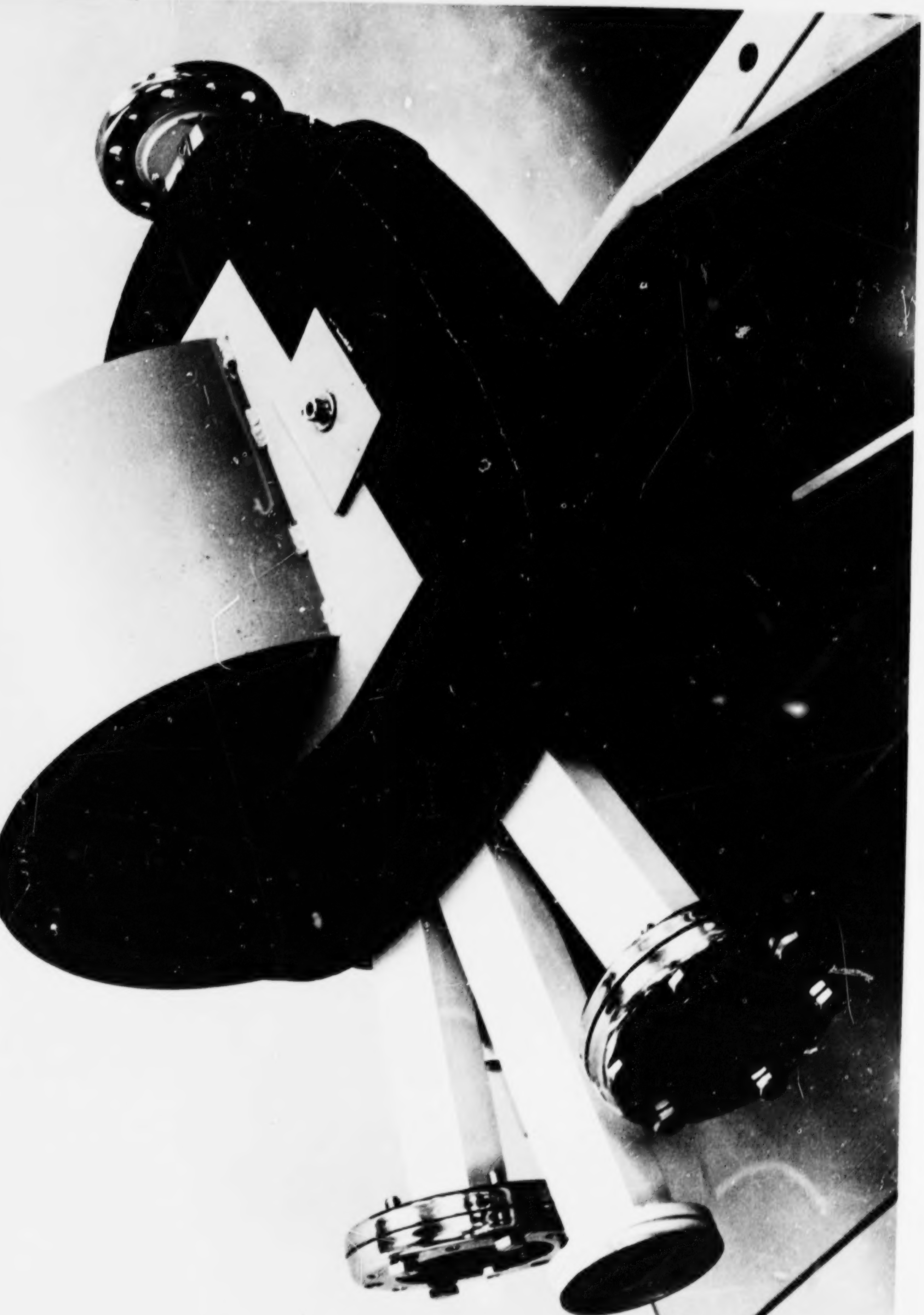


Figure 3b. Analyzing/switching magnet, $M \times E/z^2 = 0.8$

at 15°; for protons and deuterons the product 0.8 is sufficient. The stability of the power supply is better than 1% which is adequate for teaching purposes.

The scattering chamber, Figures 4A and 4B, has been designed especially for the teaching experiments. It has an internal diameter of only six inches so that it can be evacuated with the standard pump on the accelerator and it can be used for particle-γ coincidence measurements.

The beam into the chamber is collimated by a pair of horizontal slits and an aperture which are positioned in the beam tubing following the magnet chamber. A quartz viewer is placed in the wall of the chamber in a direct line with the ion beam, so that when the beam is aligned on the center of the viewer, it passes through the center of the chamber. After the beam has been aligned in this way the quartz is replaced by a Faraday cup which is electrically isolated from the rest of the chamber and the charge collected by this cup is fed via the current integrator to ground.

The target is supported on a removable aluminum target holder at the center of the chamber and can be rotated through 360° from outside the chamber. One Au-Si solid state detector is mounted on a movable arm so that its angle with the incident beam can be varied through 180° by rotating the arm from outside the chamber. The distance of this movable detector from the target can also be varied. An Au-Si solid state detector can be mounted on the wall of the chamber to monitor elastically scattered particles from the

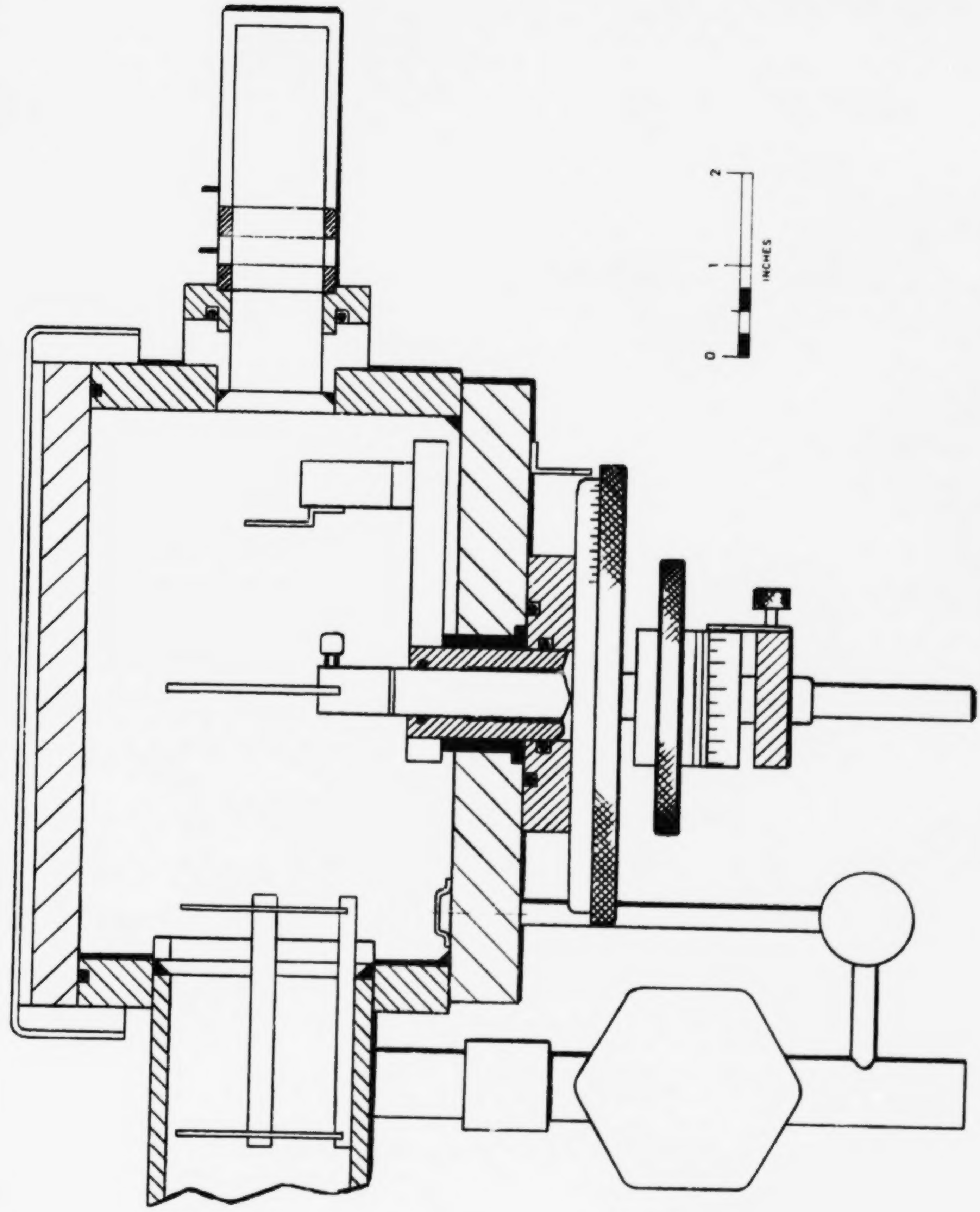


Figure 4a. Scattering chamber

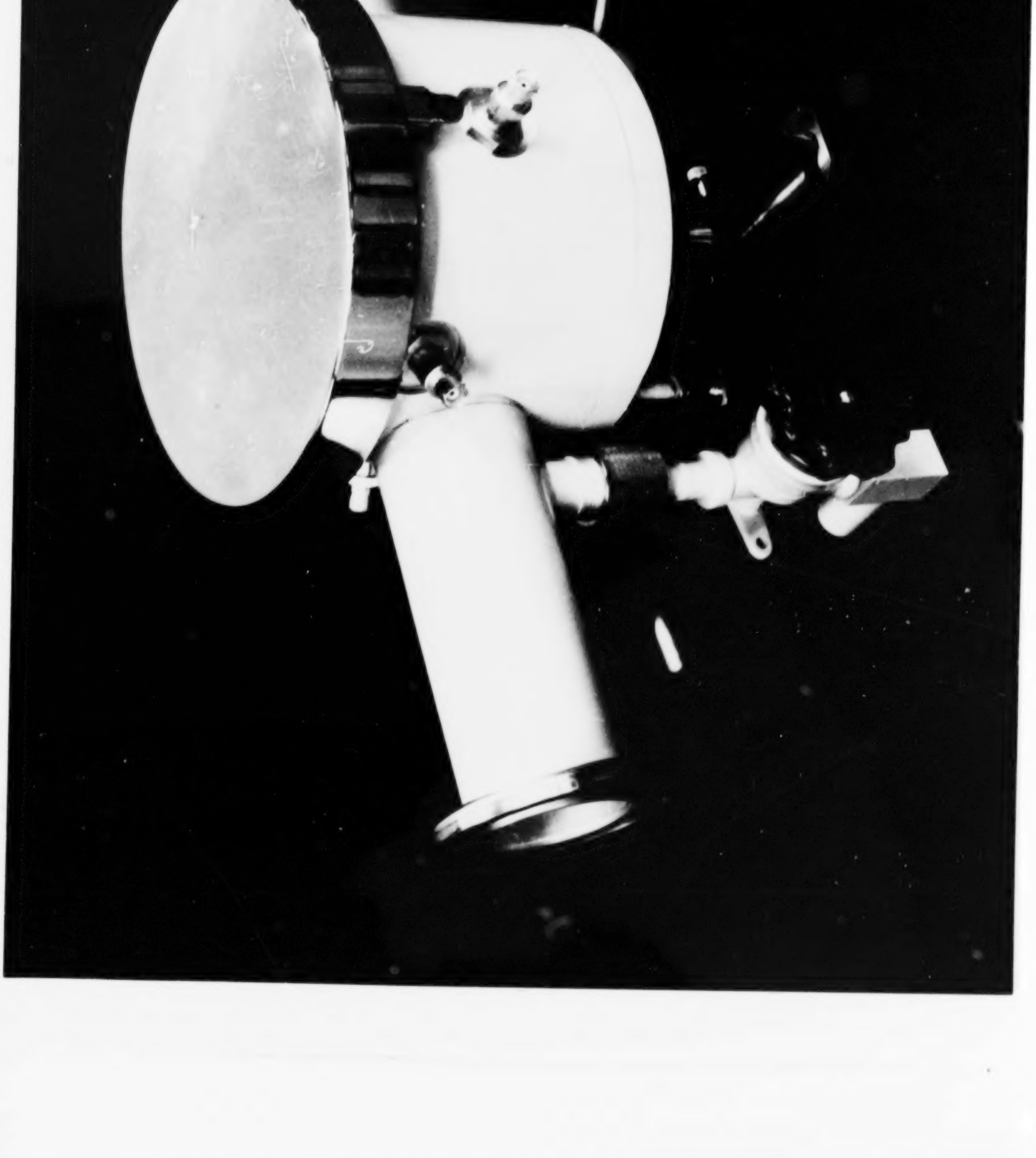


Figure 4b. Scattering chamber

incident beam; this can be placed on any of the BNC Vacuum feed-through mounts in the chamber wall.

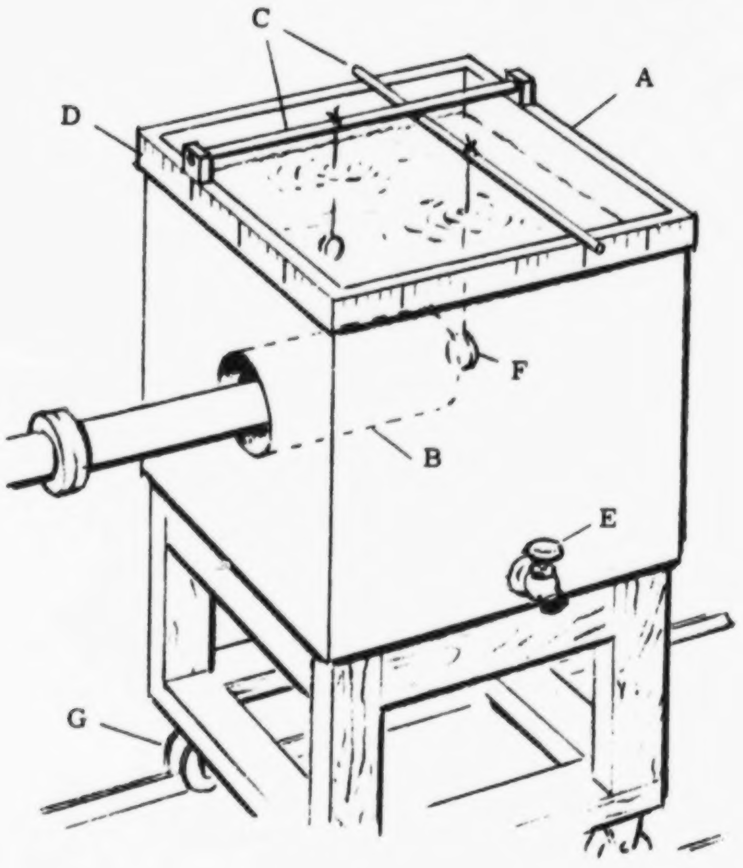
The chamber can be isolated from the accelerator by the vacuum gate valve and can be evacuated to backing pump pressures via a roughing valve. A vacuum gauge can be fitted to measure the chamber pressure during the pump-down to diffusion pump pressures.

There is a lucite top on the chamber so that the student can see the relative positions of the internal components. When the bias is on the detector, the lucite top is covered by a lid so that the chamber is light-tight.

The scattering chamber comes equipped with ten aluminum target backings with a 1/2" (1.27 cm) diameter hole in the center for self-supporting targets and ten solid backings for thick targets.

The water moderator, Figure 5, is a 24" x 24" x 24" (61 x 61 x 61 cm) cube made from lucite sheet so that the student can observe the relative positions of the activation foils within the tank. The tube B extends to the center of the moderator and the deuteron target on the end of the beam tubing is inserted into this tube so that neutrons from the $D(d,n)He^3$ reaction are produced at the center of moderator. The moderator is mounted on a trolley so that it can be moved away when the beam tube is required for other experiments.

A typical laboratory layout is shown in Figure 6. The facility requirements for the accelerator magnet and electronics are:



A - Water Tank (24" x 24" x 24") (61x61x61 cm)
B - Tube (dia. 5", length 13")
C - Rods for suspending foils
D - Scales for positioning rods
E - Draining Tap
F - Foils
G - Trolley

Figure 5. H_2O MOD Model D-TU-390 water moderator

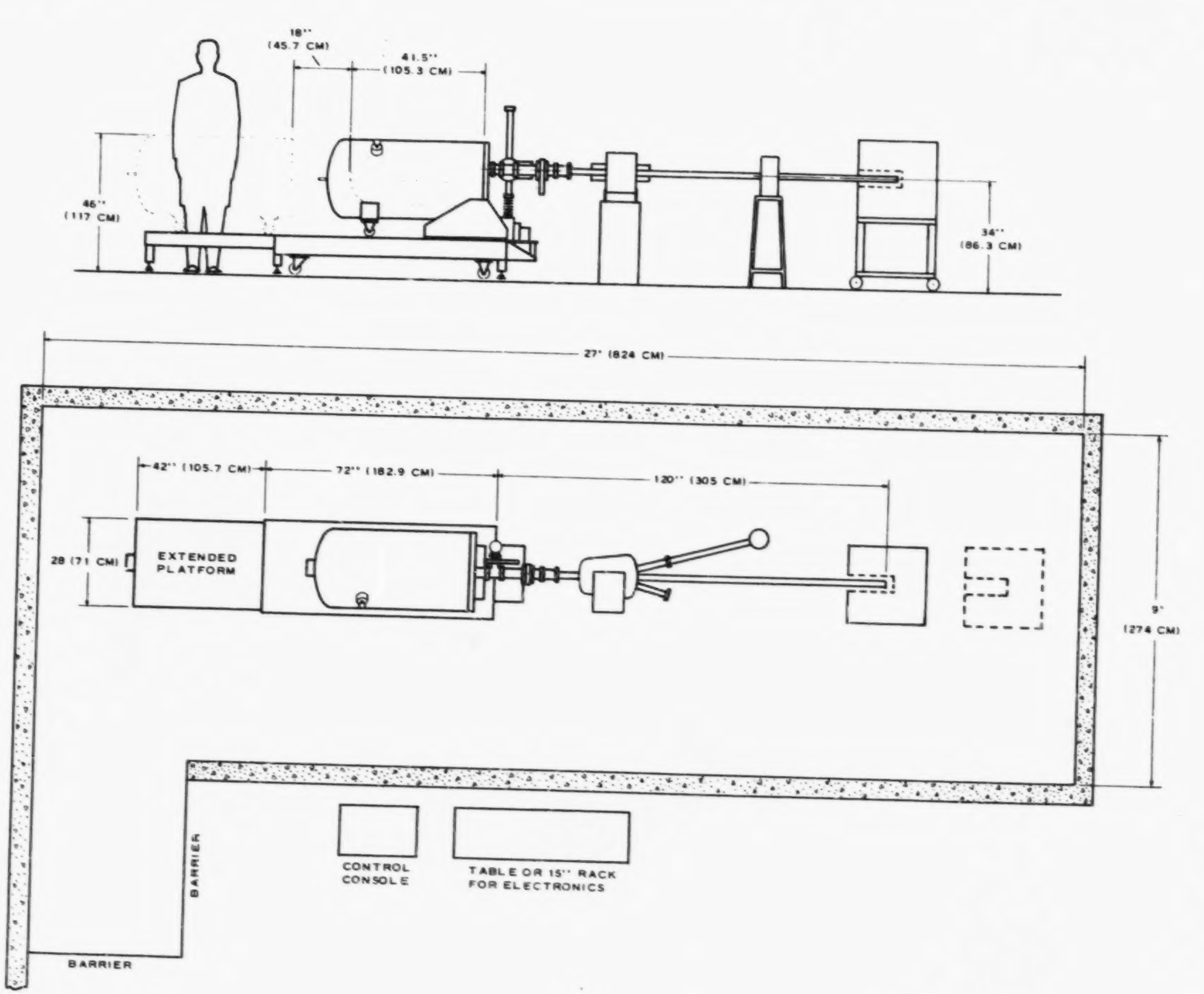

18''
(45.7 CM)
41.5''
(105.3 CM)
46''
(117 CM)
34''
(86.3 CM)
27' (824 CM)
42'' (105.7 CM)
72'' (182.9 CM)
120'' (305 CM)
28 (71 CM)
EXTENDED
PLATFORM
9'
(274 CM)
BARRIER
BARRIER
CONTROL
CONSOLE
TABLE OR 15'' RACK
FOR ELECTRONICS

Figure 6. Facility requirements (accelerator, magnet and electronics)

Electric Power:

3.0 kV-A single-phase, 120 volt 60 cycles per second. Equipment for 50-cycle current supplied upon request, 1 kV-A required continuously for the vacuum system.

Insulating Gas:

The accelerator requires a mixture of 40% nitrogen, 55% carbon dioxide, and 5% of SF_6 at 100 psig at room temperature.

Cooling Water:

1 gallon per minute, 60 psig max. at 65° F.

Refrigerant:

Liquid nitrogen, 2 liters per 8 hours for trap on diffusion pump.

Shielding:

Standard walls, floors, and ceilings of 9" concrete are sufficent for radiation shielding provided that:

(1) Only the $D(d,n)He^3$ reaction is used to produce neutrons and the target is always surrounded by a 2' x 2' x 2' (61 x 61 x 61 cm) water moderator. (This covers all of the basic set of experiments except No. 17.)

(2) The accelerator tank is covered with 1/8" (3.2 mm) lead jacket.

CAUTION: Considerably more shielding is needed if the accelerator is used to produce neutrons without a moderator of adequate size or if it is used to accelerate electrons.

TYPICAL EXPERIMENTAL RESULTS

The experimental results which are presented have been obtained at Georgetown University under the direction of Treado and Lambert. In obtaining these results, they were aware that the experiments had to be performed in one three to four hour laboratory session and the experiment should teach the student as much physics as possible in that relatively short time, so extreme accuracy was not sought. However, any of the experiments can be performed in greater depth with the same apparatus.

A few results are presented here.

Experiment No. 4. Accelerator Energy Calibration

One of the first experiments is the calibration of the 15° beam line which goes into the scattering chamber. The $F^{19}(p,\alpha\gamma)O^{16}$ reaction has a resonance at 340.5 keV with a cross-section of 160 mb with other resonances at 224 keV and 484 keV and so it is a very good reaction for energy calibration in this region. A thick fluorine target is placed in the scattering chamber and a 2" x 2" NaI detector is set to observe the 6.14 MeV gamma ray with the electronics shown in Figure 7. The discriminator is set so that the scaler only counts the 6.14 MeV, γ-ray. Figure 8 shows the γ-ray spectrum from the 2" x 2" crystal. All three peaks are due to the 6.14 MeV gamma ray: the highest energy is the total absorption peak and the other two are the escape peaks. The 340 keV resonance is found easily since the approximate voltage of the Van de Graaff terminal is known very roughly from the column currents. The excitation function for the 340 keV resonance is shown in Figure 9 as a plot of scaler counts for a given amount of charge, determined by the current integrator, against magnetic field values, determined by the magnet current. The mid-point of this thick target yield curve corresponds to 340 keV. When this energy has been established, the generating voltmeter is set to read 340 keV. The yield for the resonance at

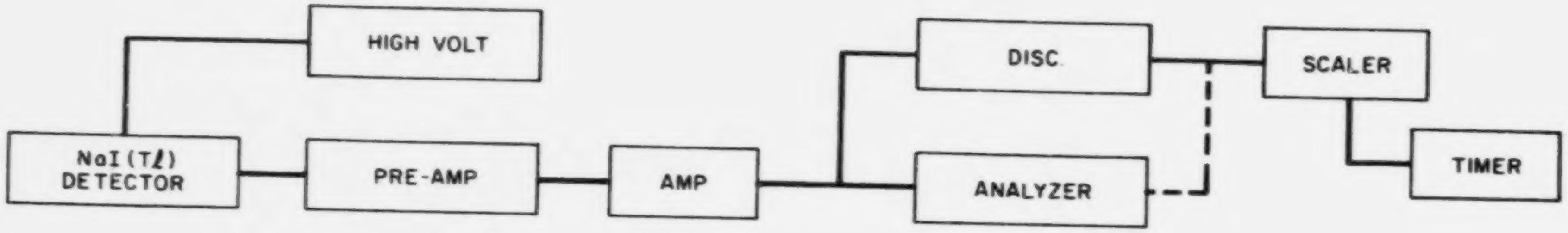

HIGH VOLT
NaI(Tℓ)
DETECTOR
PRE-AMP
AMP
DISC.
ANALYZER
SCALER
TIMER

Figure 7. Scintillation spectrometer

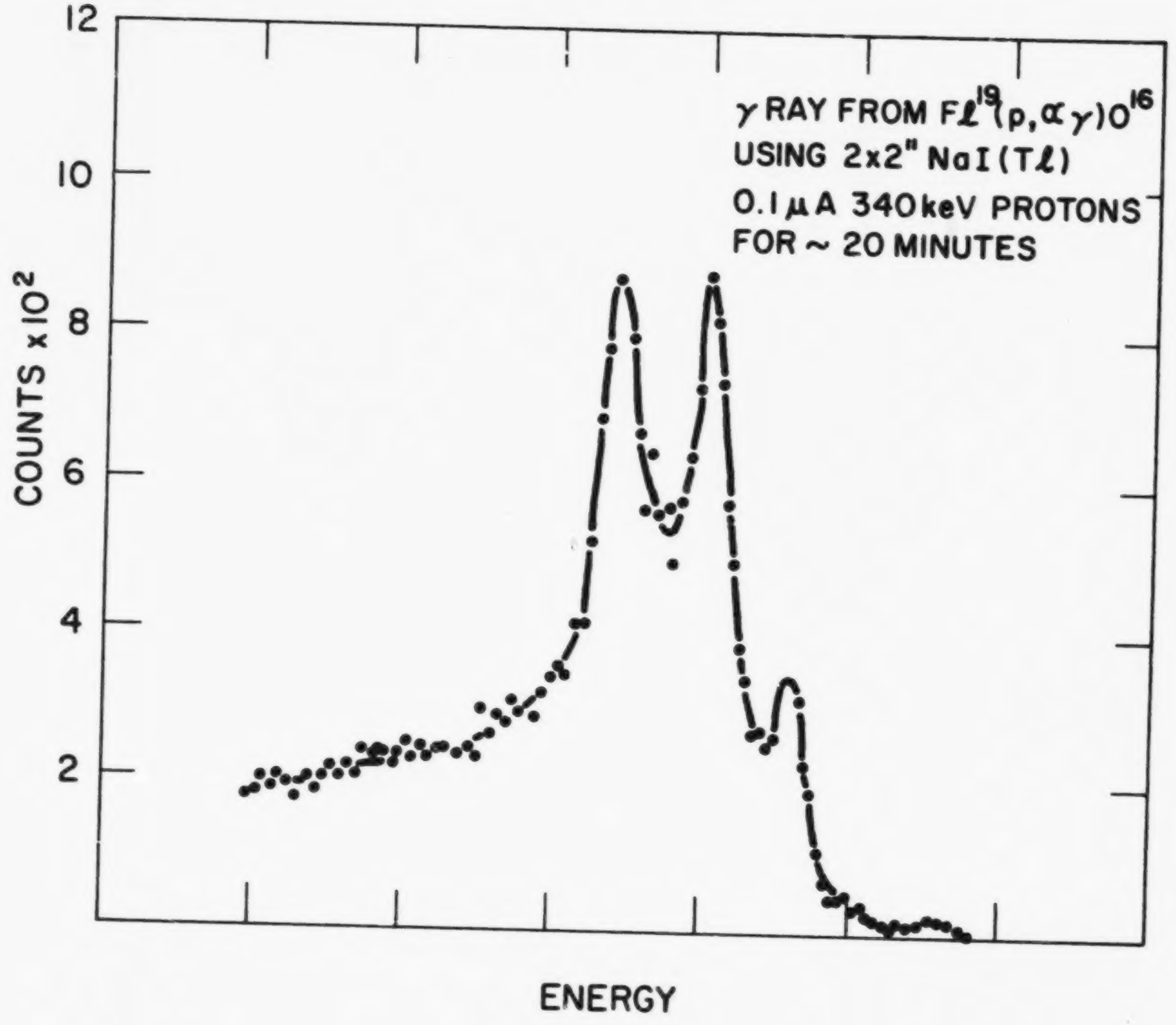

γ RAY FROM $F\ell^{19}(p,\alpha\gamma)O^{16}$
USING 2x2" NaI(Tℓ)
0.1 μA 340 keV PROTONS
FOR ~ 20 MINUTES
COUNTS x 10^2
12
10
8
6
4
2
ENERGY

Figure 8.

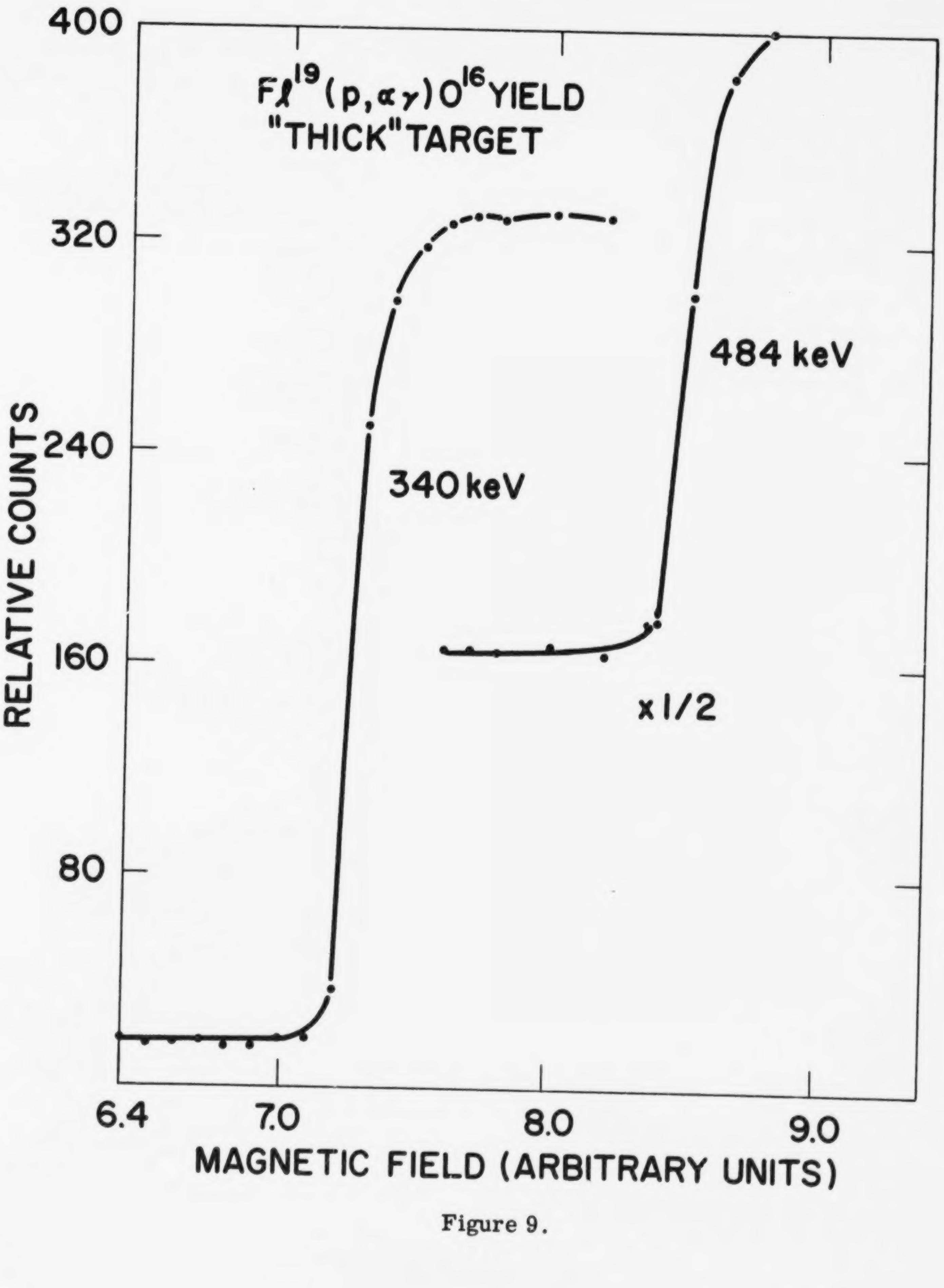

$F\ell^{19}(p,\alpha\gamma)O^{16}$ YIELD
"THICK" TARGET
RELATIVE COUNTS
400
320
240
160
80
340 keV
484 keV
x 1/2
6.4
7.0
8.0
9.0
MAGNETIC FIELD (ARBITRARY UNITS)

Figure 9.

484 keV is also shown. The much weaker resonance at 224 keV, cross-section 0.2 mb, can be found using the calibration at 340 and 484 keV. Figure 10 shows a plot of proton energy against the magnet current on a log - log plot; this has a slope of 2. This plot is used to determine the proton energies for the subsequent experiments.

Experiment No. 8. Rutherford Scattering

In principle, this experiment consists of putting a gold target in the proton beam, bombarding it with protons, counting the number of scattered protons as a function of angle and comparing this with the Rutherford scattering formula:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{e^2 Z_1 Z_2}{M_1 V_1^2}\right)^2 \frac{1}{\mathrm{Sin}^4 \frac{\Theta}{2}}$$

If very thin foils (40 $\mu g/cm^2$) are available for targets, the experiment is very straightforward, but the experiment becomes more difficult when the targets are the thinnest foils which are commercially available. The thinnest gold leaf is 5×10^{-5} cm and a 400 keV proton loses 100 keV in going through it, so it is possible to resolve the elastically scattered peak for protons which have passed through the target with its plane at 45° to the incident beam.

Another problem is the large magnitude of Rutherford cross-section. Whereas nuclear cross-sections are typically of the order of the projected area of a nucleus, i.e., in the range of 10^{-26} cm^2, the Rutherford differential cross-section at 180° for protons on

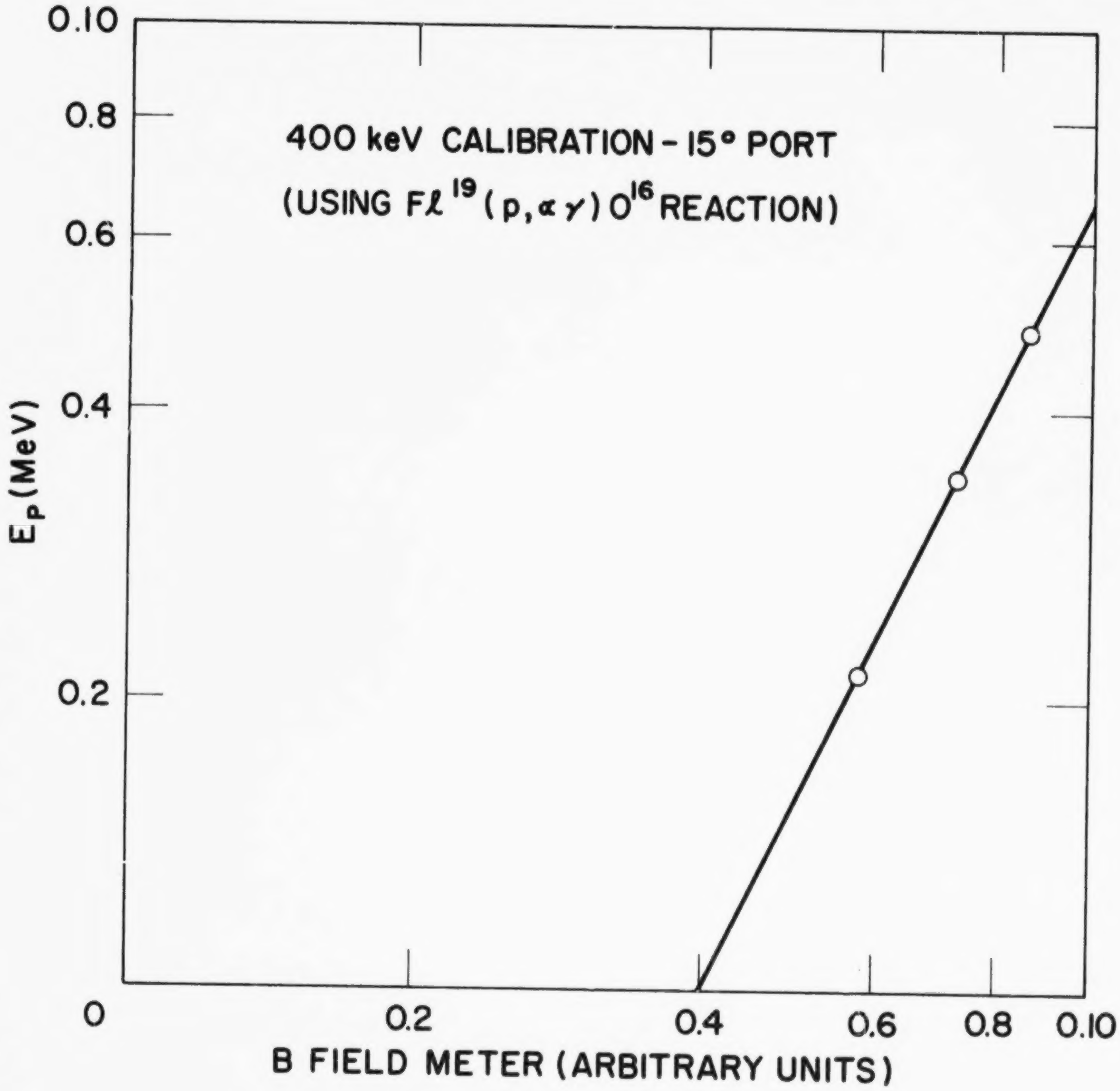

400 keV CALIBRATION - 15° PORT
(USING Fℓ¹⁹ (p, αγ) O¹⁶ REACTION)
E_p (MeV)
0.10
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
0.10
B FIELD METER (ARBITRARY UNITS)

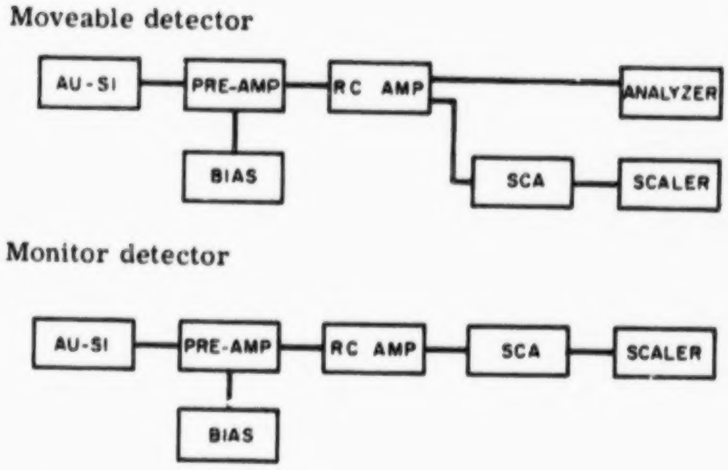
Figure 10.

gold at 400 keV is 52 barns, (1 barn = 10^{-24} cm^2) and increases to 4 times that at 90°. From Eq. (1) it can be shown that the approximate number of protons scattered by a $1/2\mu$ thick gold foil into a detector that subtends 5° at an angle of 180° is 3×10^7 per second for a 1μamp beam. It is therefore necessary to measure very small currents since most analyzers cannot handle counting rates greater than about 10^4 counts per second. There are two ways to overcome this problem: one is to mask the face of the detector to a pinhole, and the second is to put another detector in the chamber as a monitor which always counts at only one fixed angle while the movable detector counts at various angles. The latter method eliminates the need of measuring very small currents.

Figure 11 shows the electronics for this experiment with a movable detector on the rotatable arm of the scattering chamber and a monitor detector mounted on the wall of the chamber at a backward angle. The pulse height analyzer spectrum of the 400 keV protons scattered through 90° is shown in Figure 12 and Figures 13 and 14 show the experimental results.

The variation of the Rutherford cross-section with the square of the atomic number of the target can be verified by using other metallic foils such as aluminum, nickel, and silver in place of the gold.

The accuracy of the experiment can be improved by using self supporting targets which are much thinner than the commercially


Moveable detector

AU-SI
PRE-AMP
RC AMP
ANALYZER
BIAS
SCA
SCALER

Monitor detector

AU-SI
PRE-AMP
RC AMP
SCA
SCALER
BIAS

Figure 11. Semiconductor detector spectrometer

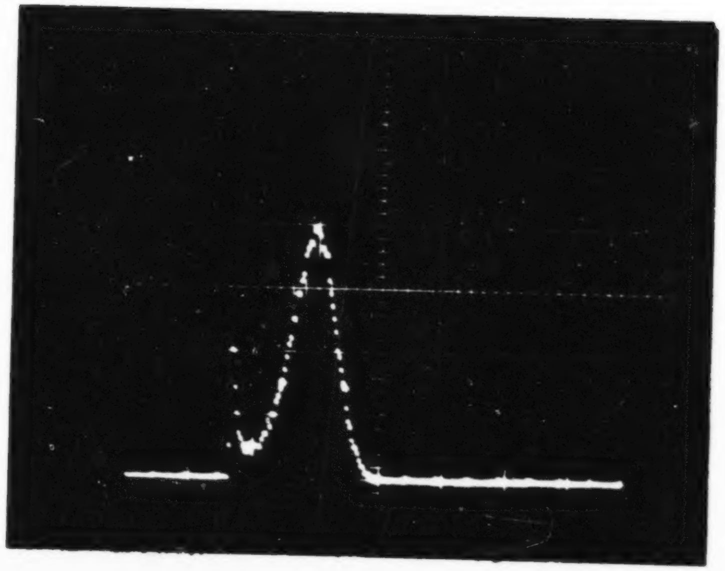


Figure 12.
RUTHERFORD SCATTERING
400 keV protons scattered through 90° from a thin gold foil

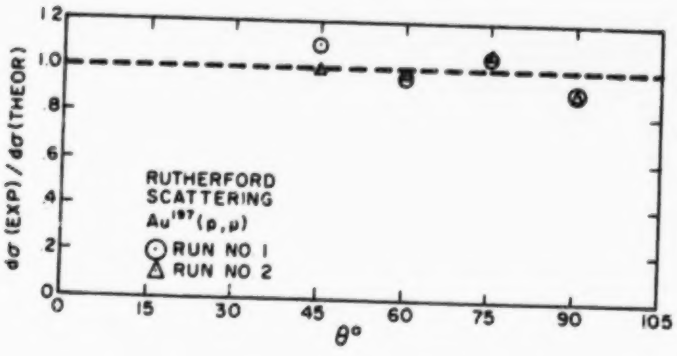


Figure 13.

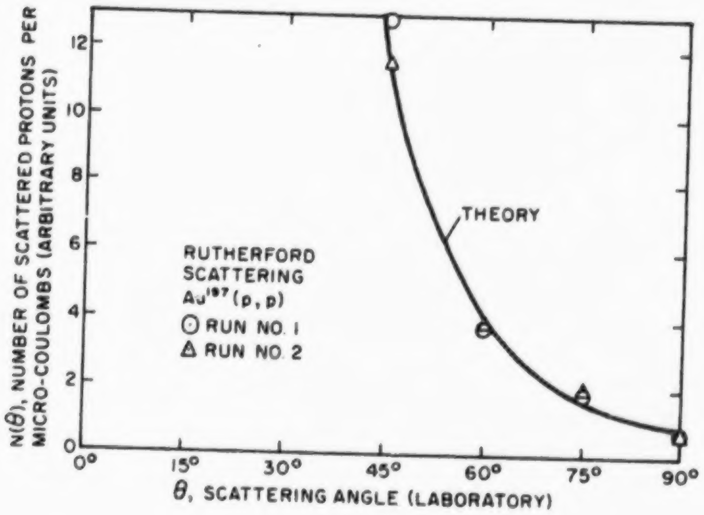


Figure 14.

available foils. These can be produced by evaporation techniques which are standard in all large nuclear structure laboratories.

Experiment No. 9. Q Value of the $Li^6(p,\alpha)He^3$ and $Li^7(p,\alpha)He^4$ Reactions

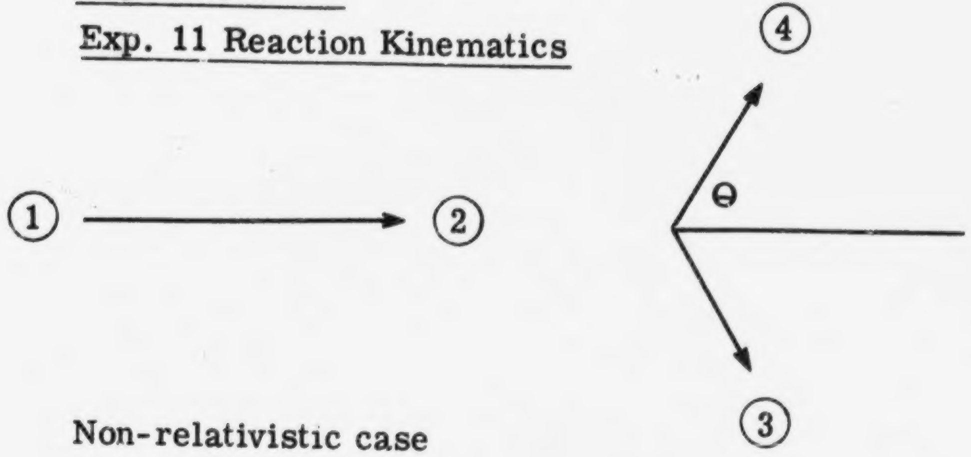
In this experiment the student repeats the classical work of Cockcroft and Walton with modern equipment so that he sees not only the $Li^7(p,\alpha)He^4$ but also the $Li^6(p,\alpha)He^3$ reaction, even though the Li^6 is only 7% abundant and he measures the energy release with a much greater accuracy than would be achieved in 1932. It is very instructive for the student to compare his experimental techniques with those which were available to Cockcroft and Walton.

Figure 15 shows the relationship between the Q value of a reaction and the masses and energies of the initial and final particles for the non-relativistic case. From this it is apparent that it is a simple matter to evaluate the Q value if the kinetic energy of particle #4 is measured at $\Theta = 90°$. It is clear that either of the outgoing particles can be called #3, and the other #4. In the reaction $Li^6(p,\alpha)He^3$, the Q value can be checked twice, since both the He^3 and alpha particle can be detected.

A thin target should be used so that particle #1 will not lose energy before interacting, and #4 will not lose energy as it is leaving the target. This cannot be achieved in practice and the actual lithium target used in these experiments had a thickness of a few hundred $\mu g/cm^2$. It was prepared by evaporating lithium on a self supporting film.

Exp. 9 Q value

Exp. 11 Reaction Kinematics



Non-relativistic case

$$Q = T_1 \left(\frac{m_1}{m_2} - 1 \right) + T_4 \left(\frac{m_4}{m_3} + 1 \right) - 2 \left(\frac{m_1 m_2}{m_3{}^2} \; T_1 \; T_4 \right)^{1/2} \text{Cos } \Theta$$

$$T_4 = A_4 + B_4 \pm \left[(A_4 + B_4)^2 - A_4{}^2 \right]^{1/2}$$

$$A_4 = \frac{(m_3 - m_1) \; T_1 + m_3 \, Q}{(m_1 + m_2)}$$

$$B_4 = \frac{2 m_1 \; m_4 \; T_1 \; \text{Cos}^2 \, \Theta}{(m_1 + m_2)^2}$$

Figure 15.

The electronics for this experiment, Figure 16, are very simple. The target is placed with its plane at 45° to the incident beam and the movable detector is placed at 90° so that the beam passes through the target before it reaches the detector.

The pulse height analyzer spectrum is shown in Figures 17 and 18.

Natural Li is only 7% of Li^6 and 93% of Li^7, so there are contributions from both $Li^7(p,\alpha)\alpha$, and $Li^6(p,\alpha)He^3$. The highest energy peak, A, is due to alphas from Li^7, B is the He^3 from Li^6, and C is the α from Li^6. The fact that A comes from Li^7 could be verified by using different targets that were enriched in Li^6, and observing the height of A relative to B and C. It will be assumed that this has been done.

At this time the identity of B as a He^3, and C as an alpha is assumed known. Actually this is proved in a later experiment in which the identity of the particles are checked by the kinematics of the reaction. Another method of identifying the particles would be to place foils of known thickness over the Au-Si detector and observing the change in the spectra.

The energy calibration is made at 5.47 MeV with an Am^{241} source and a pulse generator is used to determine the analyzer channel corresponding to zero energy.

The energies of peaks A, B, and C determined from this calibration are: 1.7, 2.35 and 8.75 MeV respectively, and the

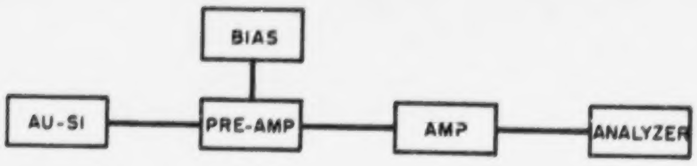

BIAS
AU-SI
PRE-AMP
AMP
ANALYZER

Figure 16. Semiconductor detector spectrometer

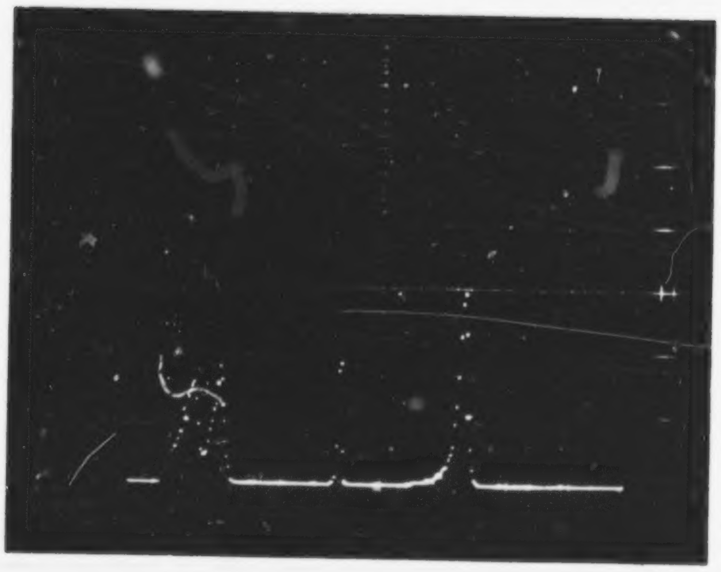


Figure 17.
REACTION Q VALUE
Products from $Li^6(p,\alpha)He^3$ and $Li^7(p,\alpha)He^4$ reactions.

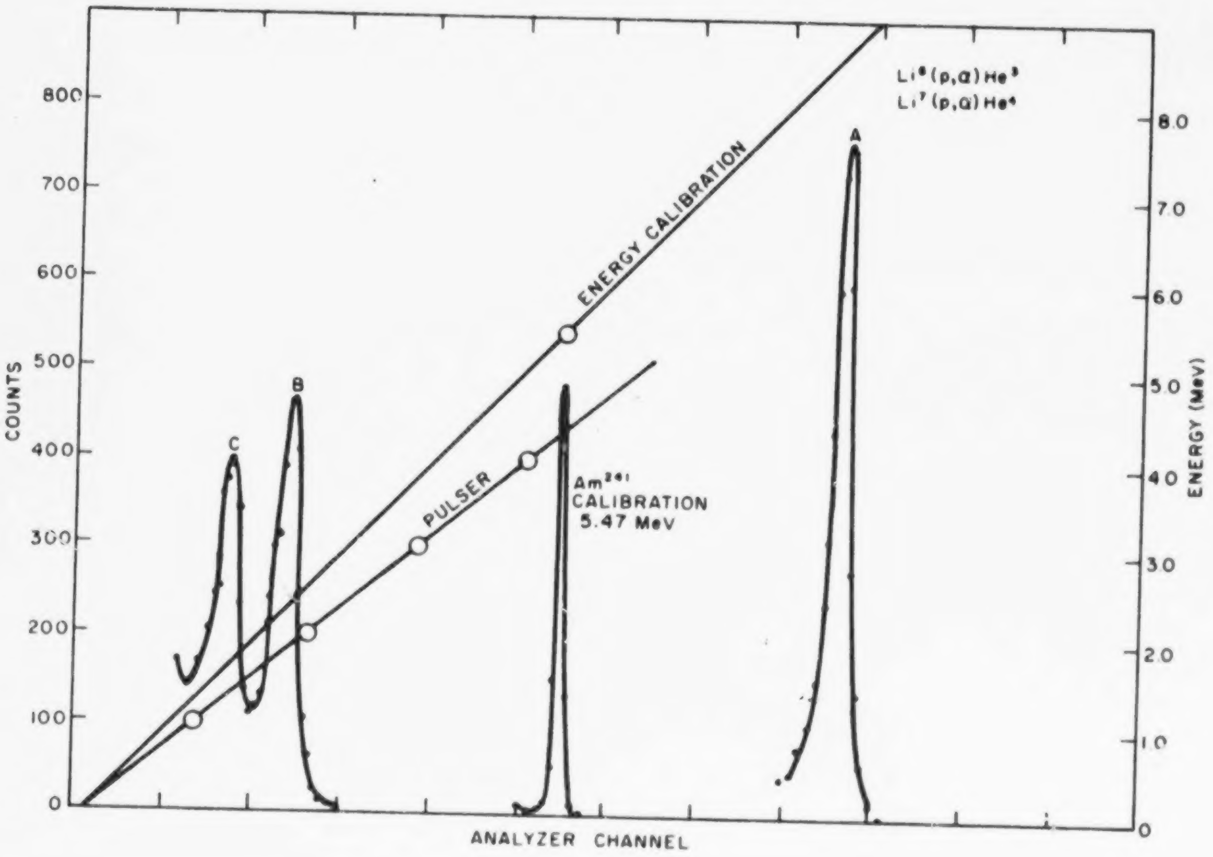

$Li^6(p,\alpha)He^3$
$Li^7(p,\alpha)He^4$
A
B
C
ENERGY CALIBRATION
PULSER
Am^{241}
CALIBRATION
5.47 MeV
COUNTS
0
100
200
300
400
500
600
700
800
ENERGY (MeV)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
ANALYZER CHANNEL

Figure 18.

energy of the incident proton is known to be 330 keV from the magnet calibration of experiment 4. After corrections have been made for the energy losses of the ingoing and outgoing particles, the following Q values in Figure 19 are obtained.

The student should use a table of atomic masses to show that this energy release is equal to the mass difference between the initial and final nuclei. This was the actual experiment performed by Bainbridge in 1933 to verify the equivalence of energy and mass.

Experiment No. 11. Kinematics of the $Li^6(p,\alpha)$ and $Li^7(p,\alpha)He^4$ Reactions

The relationship between the kinetic energy of the particles produced in a nuclear reaction is given in Figure 15. In this experiment the same experimental techniques as the 'Q' value measurement, experiment No. 9, are used to measure the kinetic energy of the outgoing particles and so verify the kinematics of the reaction. Figure 20 shows the spectra taken at three angles: 44°, 90°, and 148°. In a more detailed analysis, T_4 is plotted as a function of angle for the particles and this is compared with the experimental results. So the particles involved in the reaction are identified.

Experiment No. 16. Alpha-Gamma Coincidences in the $F^{19}(p,\alpha\gamma)O^{16}$ Reactions

This experiment demonstrates the coincidence technique of nuclear spectroscopy. A thin fluorine target on a nickel backing is placed in the scattering chamber at 45° to the incident beam with

RESULTS EXPERIMENT NO. 9

$Li^6(p, \alpha)He^3$ (a) from He^3 energy $Q = 3.92$ MeV (4.022)
(b) from He^4 energy $Q = 4.02$ MeV

$Li^7(p, \alpha)He^4$ $Q = 17.3$ MeV (17.347)

Figure 19.

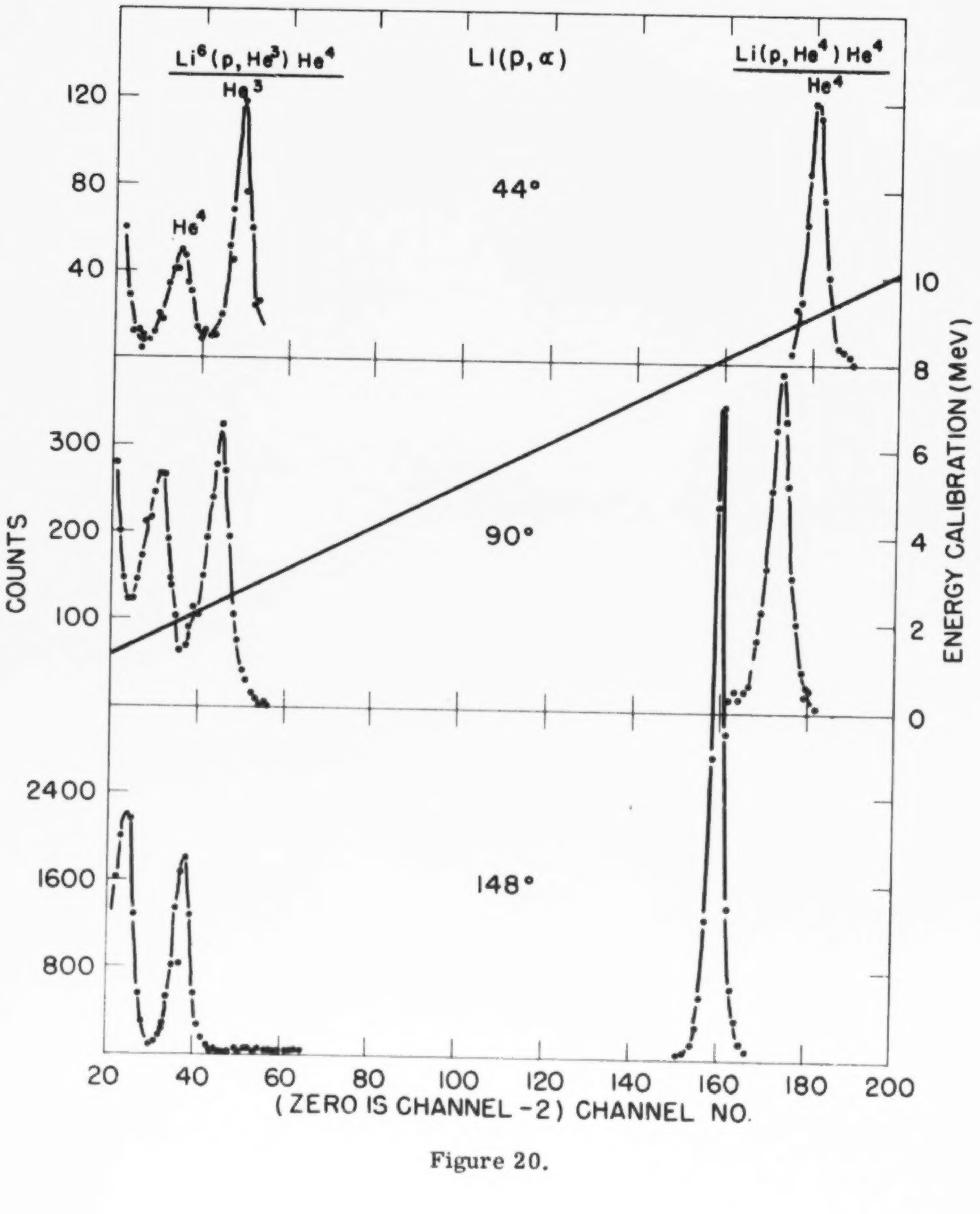

Li^6(p, He^3) He^4
He^3
He^4
LI(p, α)
Li(p, He^4) He^4
He^4
44°
90°
148°
120
80
40
300
200
100
2400
1600
800
COUNTS
10
8
6
4
2
0
ENERGY CALIBRATION (MeV)
20
40
60
80
100
120
140
160
180
200
(ZERO IS CHANNEL -2) CHANNEL NO.

Figure 20.

the movable Au-Si detector at 90° and a 2" x 2" NaI (Tℓ) detector outside the chamber at 45°.

An excitation function is measured for the 340 keV resonance which has a width of approximately 3 keV, and the proton energy is then set at the peak of this excitation function.

The observed resonance is a state in the compound nucleus Ne^{20}. Since the proton is bound to F^{19} with 12.873 MeV to form Ne^{20}, and the proton $- F^{19}$ system has $\frac{19}{20}$ (340) = 323 keV in the center-of-mass system, the 340 keV resonance corresponds to an energy level of 13.196 MeV in the Ne^{20} system. It has been found experimentally that this state decays predominantly through the 6.14 MeV level of O^{16}.

The reaction is the following:

$$F^{19} + p \longrightarrow O^{16*} + \alpha + 1.979 \text{ MeV}$$

$$O^{16*} \longrightarrow O^{16} + \gamma + 6.14 \text{ MeV}$$

the lifetime for the emission of the γ-ray is so short ($\tau \sim 10^{-11}$ sec) that it is possible to observe the α particle and the γ-ray in coincidence. For the reaction $F^{19}(p,\alpha)O^{16}$ to the ground state of O^{16}, the Q is 8.119 MeV, whereas in the reaction to the 6.14 MeV state of O^{16*}, there is much less energy available for the particles so the Q value is 1.979 MeV. So an α emitted at 90° to the beam should have an energy of 1.84 MeV when the proton energy is 340 keV.

To observe this, the electronics in Figure 21 are used. The SCA on the Au-Si detector is set at 1.84 MeV and the SCA on the

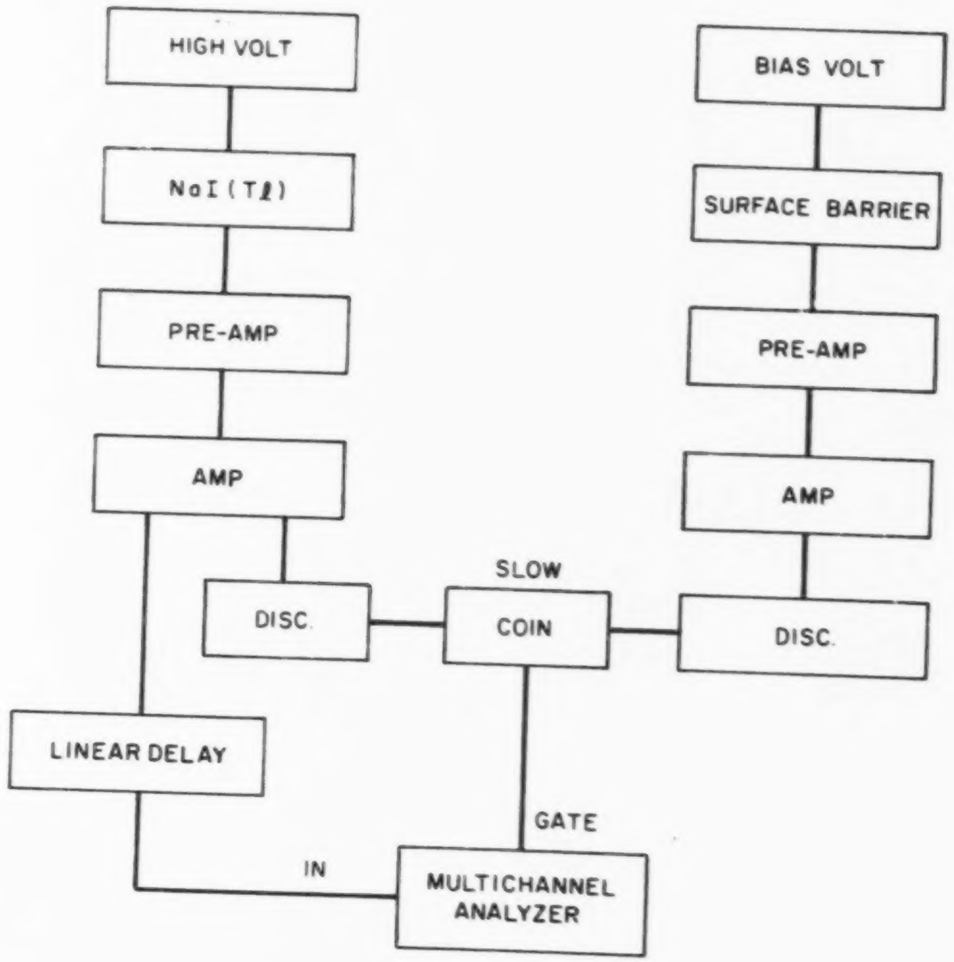

HIGH VOLT
NaI (Tℓ)
PRE-AMP
AMP
DISC.
LINEAR DELAY
IN
SLOW
COIN
GATE
MULTICHANNEL ANALYZER
BIAS VOLT
SURFACE BARRIER
PRE-AMP
AMP
DISC.

Figure 21. Coincidence spectrometer

NaI detector is set to trigger on any γ-ray. The two SCA outputs are fed into the slow coincidence unit, and this output gates the multi-channel analyzer displaying the γ-ray spectrum. A coincident spectrum is shown in Figure 22.

Although it is not done in this experiment, everything is now set up to measure any angular correlation and assign the spins and parities of the states in Ne^{20} and O^{16}.

CONCLUDING COMMENTS

The apparatus and experimental techniques form a good foundation for a laboratory which wants to start a nuclear structure research facility in addition to teaching. The whole laboratory can be expanded as the research interest grows by increasing the basic line of equipment.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the collaboration of Dr. Paul Treado and Dr. James Lambert at Georgetown University, Washington, D. C. in the preparation of the material contained in this paper.

WB:hts
March 27, 1969

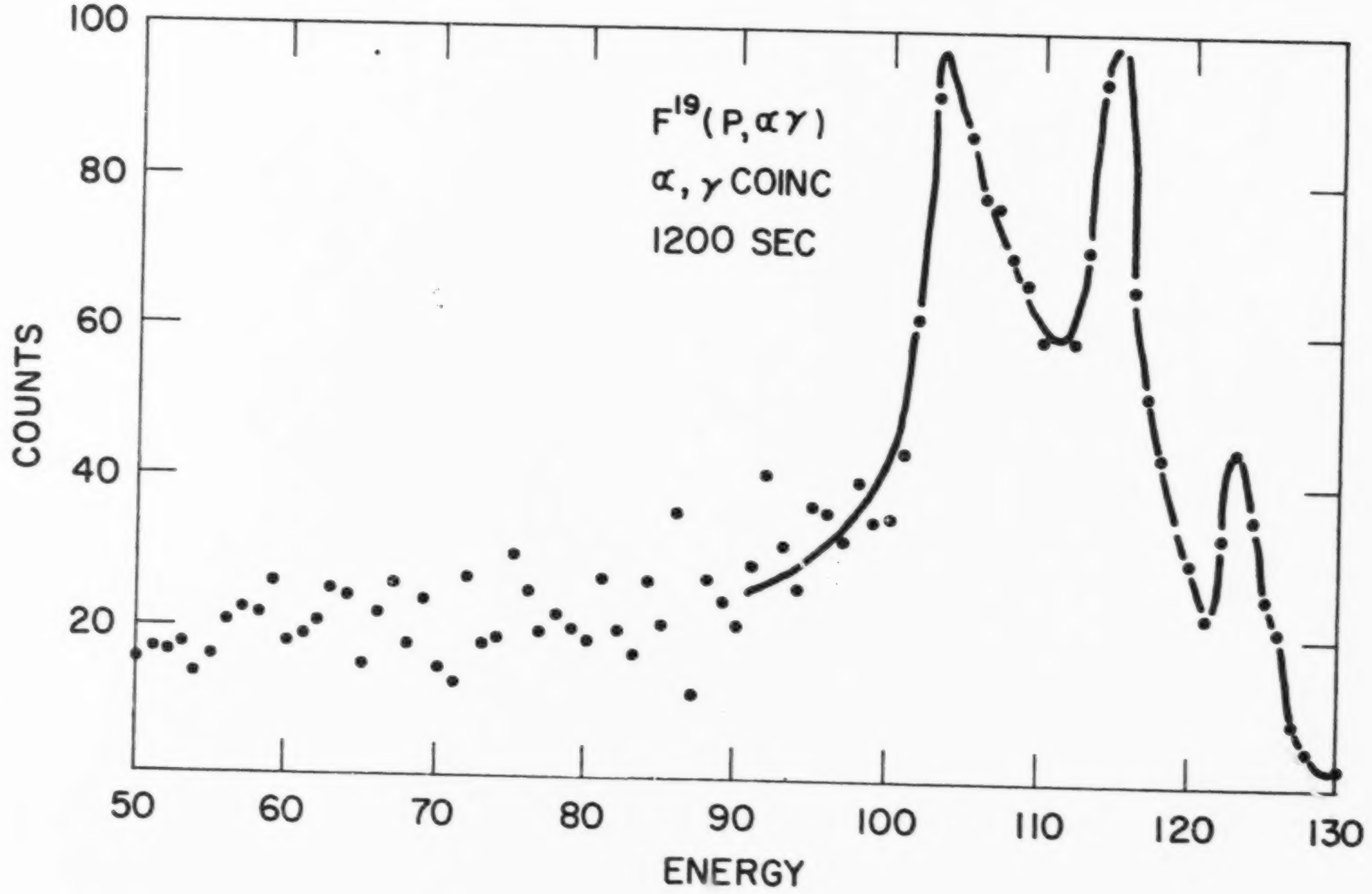

$F^{19}(P,\alpha\gamma)$
α,γ COINC
1200 SEC
COUNTS
100
80
60
40
20
ENERGY
50
60
70
80
90
100
110
120
130

Figure 22.

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3. P. A. Treado and J. M. Lambert, Am. J. Phys. 36, 987 (1968).
4. Research Trends, 1962-1967, Nuclear Structure Physics (Nuclear Science Foundation Publication NSF-62-45).
5. Modern Physics Laboratory Manual (Canberra Industries, Middletown, 1968).
6. Laboratory Manual A, R. T. Overman (Ortec, Oak Ridge, 1967).

THE IMPORTANCE OF THE LOW ENERGY ACCELERATOR IN THE SMALL UNDERGRADUATE PHYSICS DEPARTMENT

by

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Valparaiso University

Valparaiso, Indiana

ABSTRACT

For the small university that wishes to excell in undergraduate training, or exceptional preparation for graduate study, the low energy accelerator with some allied equipment seems to be a must. These accelerators together with the new modular electronic equipment enables one to do many of the classical experiments with good results in relatively short periods of time. The equipment used at Valparaiso University and one of these experiments will be described giving actual data as obtained in the student laboratory. Two other laboratory instruction sheets are included.

INTRODUCTION

Perhaps ten or fifteen years ago the small undergraduate university could not afford financially nor did it have the space in its physical plant for an accelerator. Most of the units at that time were custom built and the costs both for installation and operation were prohibitively high. With the development of the small accelerators and new modular equipment instead of the cumbersome tube assemblies, the picture has changed.

Furthermore, present day students on the junior and senior college level are anxious to do some of the classical experiments rather than just to see a description of them on the blackboard. There is no better way to whet the appetite of students for further research than by actual laboratory work involving Rutherford scattering, Compton scattering, Q-values, neutron studies, etc.

In 1957 Valparaiso University embarked on the development of a rather extensive laboratory program involving both the junior and senior physics majors, and also those engineering students taking introductory reactor training. These students now perform some twenty to twenty-five advanced laboratory experiments and many of them work on an individual laboratory research problem as well. These experiments revolve around an accelerator, a scattering chamber, and a sub-critical reactor. The accelerator alone without some allied equipment, as, for example the scattering chamber, would not justify the cost to the small university.

THE EQUIPMENT

Our selection of an accelerator was determined by the fact that in performing some of the sub-critical reactor experiments large beam currents are necessary. It is for this reason that we selected a 300 KV Texas Nuclear Accelerator with a switching magnet as a replacement of our former 150 KV machine. This accelerator (Figures 1 and 2), capable of producing several hundred microamps with ease, can also be pulsed with a repetition rate of up to (4 x 10^6) PPS with a pulse variable from 1 to 10^6 microseconds. By using a steering magnet we can shift the beam from the reactor to the scattering chamber without opening the vacuum system. (Figure 3)

The scattering chamber (Figure 4) was built after the design used at Oak Ridge[1] and was made locally from a solid bronze casting. In this way we have never suffered from the problems of outgassing from welded seams. It is about fourteen inches in diameter and seven inches deep. Perhaps this may seem rather large especially from the viewpoint of a vacuum system, but actually due to the careful machining of the chamber by our engineering school, vacuum has not been a problem.

This fast pump down system using two large mechanical pumps and one diffusion pump enables one to make some adjustments in the chamber and again be able to operate in about fifteen to twenty minutes. In this way we have tried to eliminate or minimize the monotonous periods of waiting which I am sure neither the students

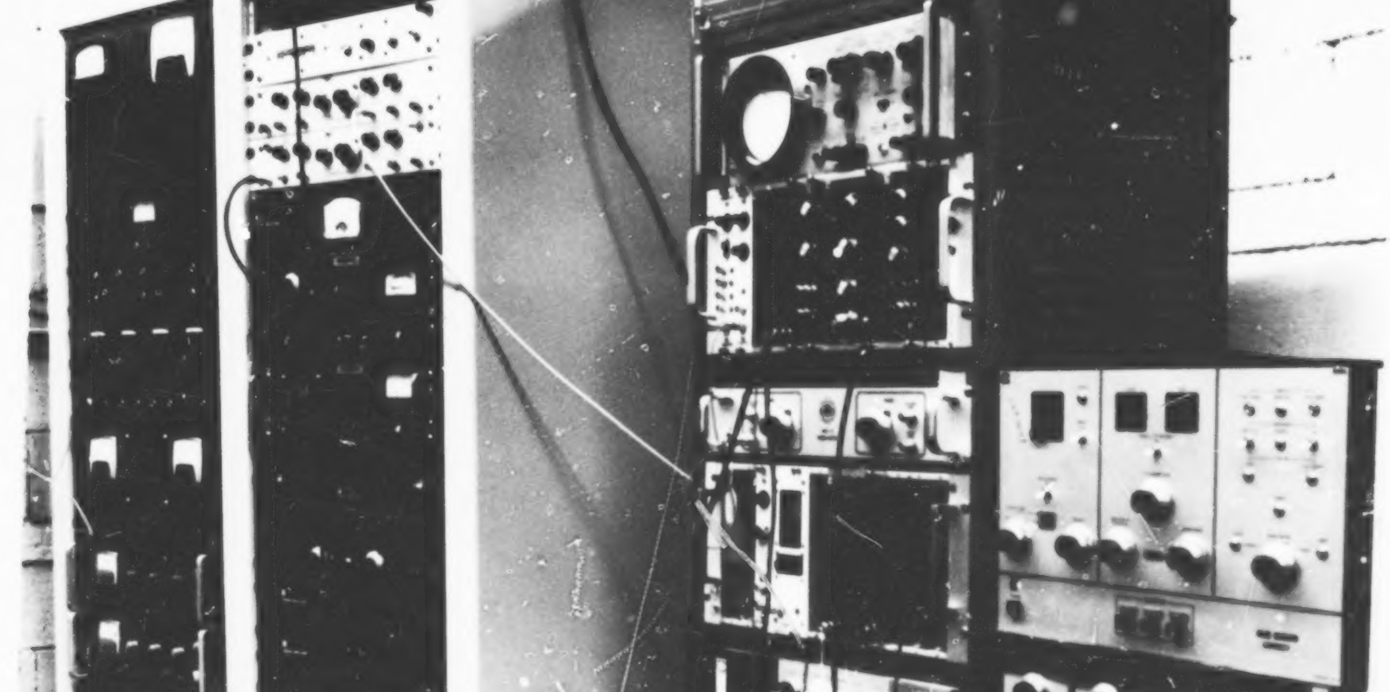


Figure 1

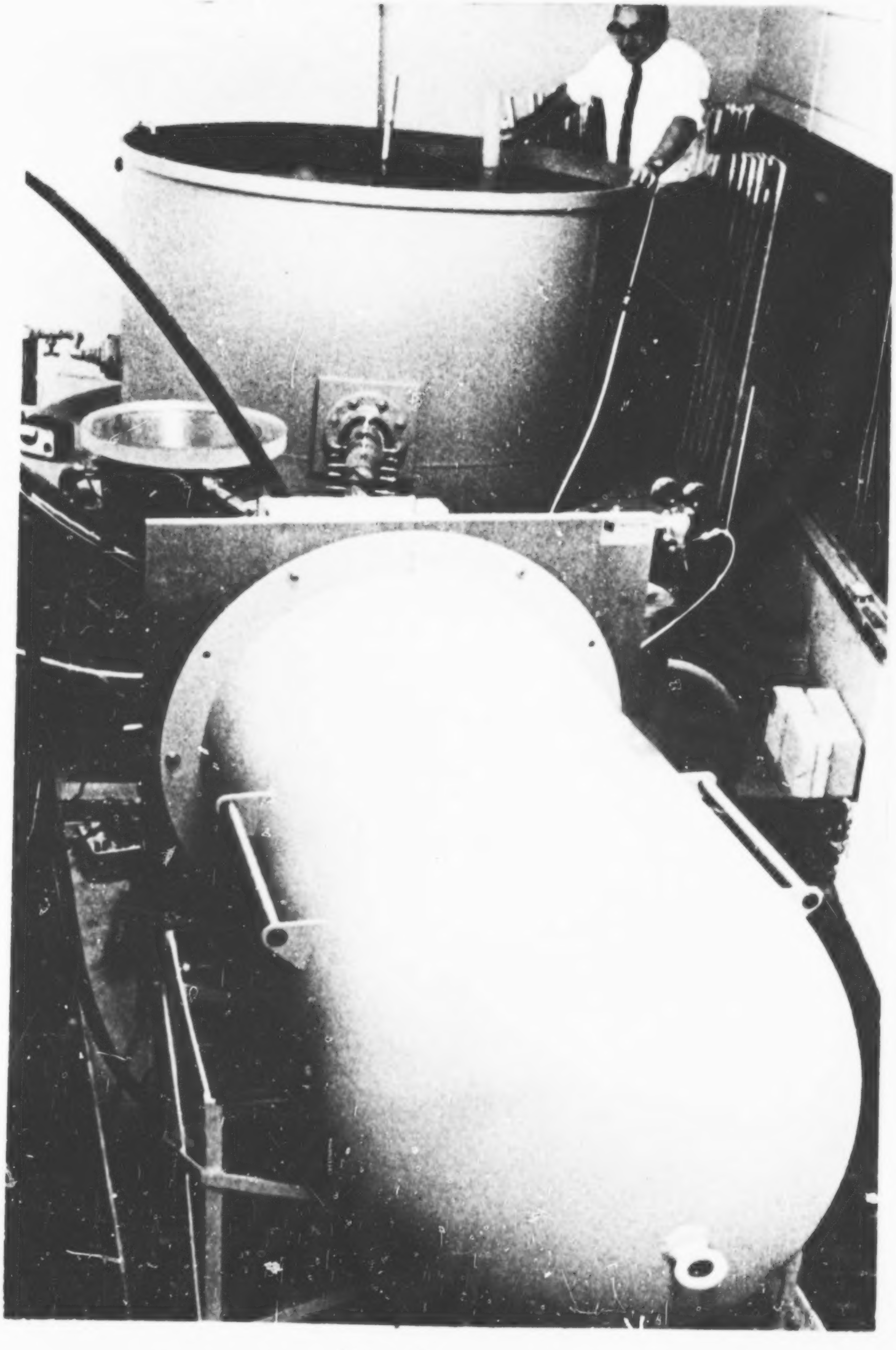


Figure 2

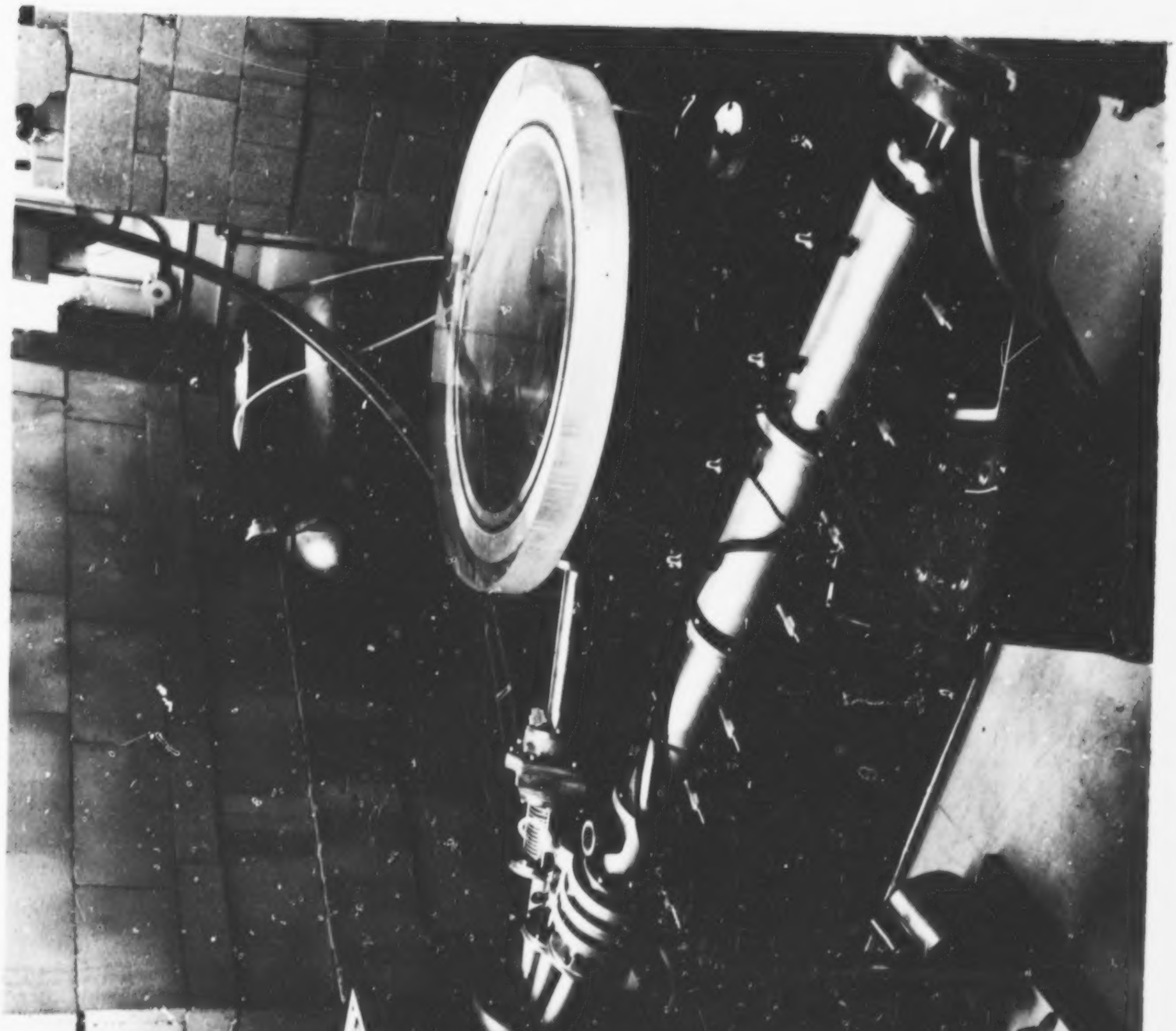


Figure 3

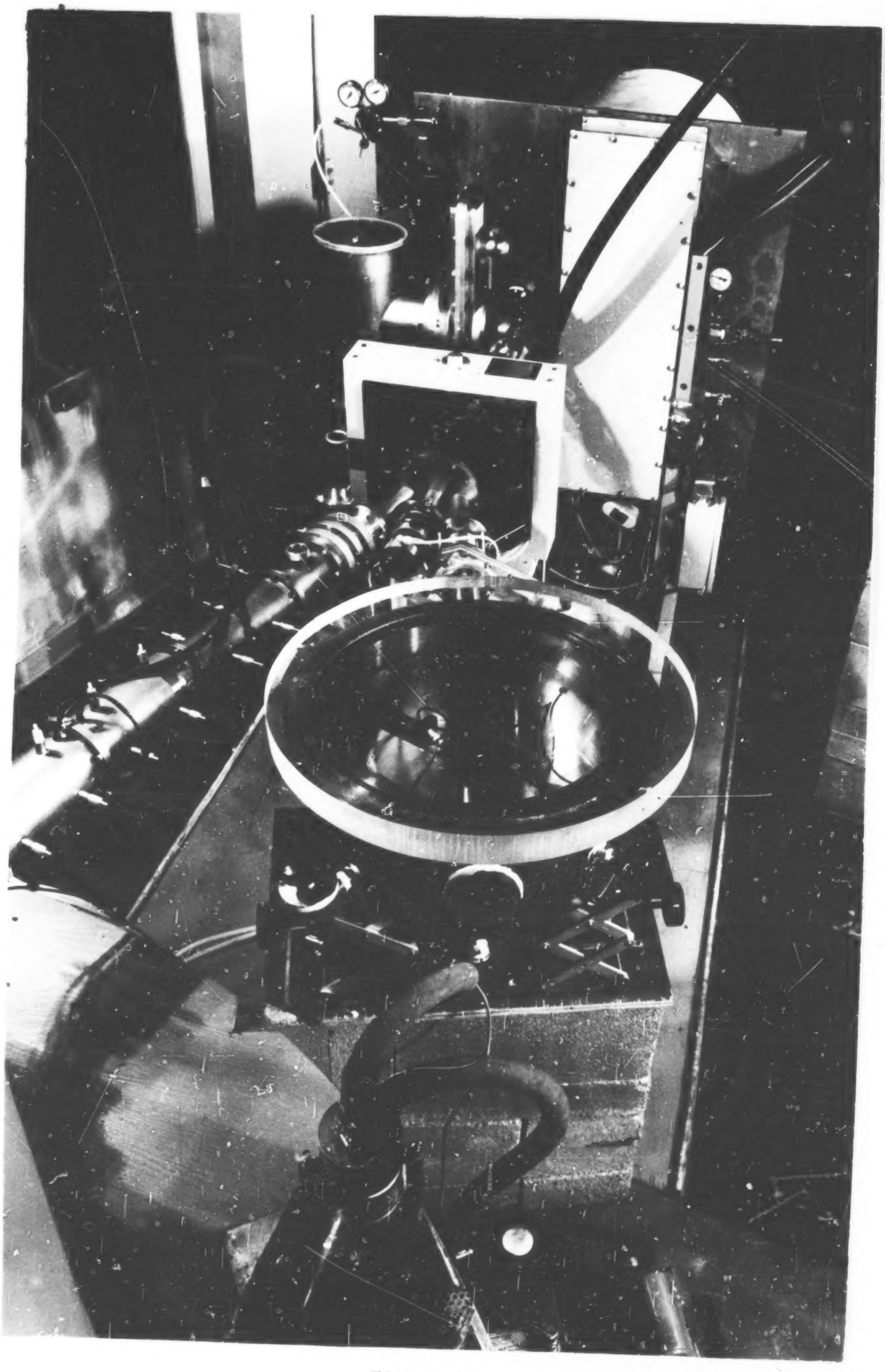


Figure 4

nor the instructor enjoy. There is some advantage to the large chamber in that experiments other than those involving the accelerator can be performed (e.g., ionization studies, particle range with various gases at different pressures, etc.).[2,3,4,5]

The Valparaiso sub-critical reactor has a tank six feet in diameter containing about 1000 gallons of water. When loaded it contains 2500 kilograms of natural uranium with some 286 rods.

The necessary supplementary equipment includes a number of power supplies, scalers, single channel analyzers, a linear amplifier, and a multi-channel pulse height analyzer which can also be used in the time sequence mode. The list of experiments which can be performed with this equipment is rather long and many of these have been reported in the literature.[6,7,8,9,10,11] One could start with an introduction of accelerator design, study the magnetic fields, go on to scattering experiments, Q-values, energy levels, activation studies, crystal structures, neutron studies, sub-critical reactor analysis, etc. A list of the experiments performed by our junior and senior students using this equipment is given in Table I.

LABORATORY EXPERIMENTS

Time and a definite schedule are important in a teaching laboratory. One cannot drag out an experiment for days and days nor run over into other class periods. Therefore we try as much as possible to limit our laboratory periods to three or four hours, but sometimes, of course, these must run longer. Laboratory sheets which we prepare for our students are but very brief statements of the experiment containing just sufficient introductory material. Our objective in this procedure is to force the student to look up several references, in some cases original papers, before coming to class rather than follow the "cookbook" system which seems so necessary in the freshman laboratory. In this way the students receive a wider picture of the whole subject and, in being forced to page through the journals, acquire a greater appreciation of the entire research field. Three of these laboratory instruction sheets are found in the following pages. An experiment which is not so widely reported as others is a measure of the mean life of neutrons in water. This experiment is the first pulsing experiment done with the students and the actual results are given.

TABLE I

(Experiments available to students using the equipment mentioned in this paper. Note: undergraduate only.)

1. Neutron Activation Studies
2. Rutherford Scattering (various target materials--alphas, protons, and deutrons)
3. Q-Value Studies using $Li^7(p,\alpha)He^4$
4. The Li^6 Studies with Deutrons
5. Measurement of Short Half-Lives
6. Gamma-gamma Coincidence Studies
7. The Mean Lifetime of Neutrons in Water
8. Thermal Neutron Cross-section Measurements
9. The Critical Approach (reactor experiment)
10. Determination of the Prompt Multiplication Factor
11. A Study of Moderator Fuel Ratios
12. Control Rod Effect
13. Measure of Thermal Neutron Diffusion Length
14. Neutron Flux Distribution in Reactor Tank
15. Special Student Projects

Note: In doing the above experiments the students likewise become acquainted with vacuum systems and problems, the accelerator system, electronic problems, detectors, shielding, etc. Rather than having individual experiments on these subjects, they are explained to the group as required (during long counting periods).

THE MEASUREMENT OF THIN METALLIC FOILS AND THE USE OF THESE FOILS IN A RUTHERFORD SCATTERING EXPERIMENT

This experiment is actually a combination of two experiments and will be performed over several laboratory periods. The first part consists of measuring the thickness of several very thin foils following the dE/dX method and then using these foils to scatter protons or deutrons.

When a charged particle passes through a foil it will lose energy. This loss is dependent upon the material of which the foil is made, its thickness, and the energy of the bombarding particle.

The procedure to be followed in this experiment is a rather simple one. After the multi-channel analyzer has been calibrated, a thin foil will be placed in the scattering chamber perpendicular to the beam and the loss in energy noted. Using then the dE/dX tables as given in the 1960 Nuclear Data Tables, Part 3 published by the United States Atomic Energy Commission, the thickness can be determined. Once the thickness has been measured, this foil will be used in scattering charged particles.

Scattering experiments involving the elementary particles serve as an important means of investigating the nature and strength of forces existing between a nucleus and a bombarding particle. The forces which might come uder consideration are gravitational, electromagnetic, short-range strong nuclear forces holding the nucleus together and weaker forces involved in radioactive decay. In these scattering experiments the electromagnetic forces are the only ones which will be considered because the bombarding particles will not have sufficient energy to overcome the repulsion of the coulomb potential and hence nuclear forces will play no part.

In this study charged particles will be scattered from thin foils of Au, Cu, and C. The development of the scattering formula can be found in almost any book on modern physics and will not be repeated here. The ratio of Z values is given below:

Z = atomic number of the scatterer

Y = total number of charged particles scattered per unit area at one angle

n = atoms per unit volume

t = thickness of scattering material

$$\frac{Z_1}{Z_2} = \frac{\sqrt{Y_1\, n_2\, t_2}}{\sqrt{Y_2\, n_1\, t_1}}$$

In this ratio method of verification, correction factors can be eliminated since the experiment is performed under the exact same conditions.

The angles of scattering will be limited to those which will give a reasonable count in a short period of time in order that the entire experiment may be completed in two laboratory periods. The three foils will be used in the same positions and the Z ratios compared with accepted values.

Consult the following references before performing the experiment.

1. Kaplan, *Nuclear Physics*, Addison-Wesley Publishing Co.
2. Evans, R. D., *The Atomic Nucleus*, McGraw-Hill Book Co.
3. Arya, A. P., *Fundamentals of Nuclear Physics*, Allyn and Bacon.

Your report is to include:

1. The development of the "ratio formula" starting with the Rutherford Scattering Law;
2. A comparison of experimental and computed values; and
3. A comparison plot of experimental and theoretical values.

A STUDY OF THE $Li^7(p,\alpha)$ REACTION

An important principle which must be understood in particle interaction and energy-mass equivalence becomes quite apparent in this Q-value experiment. The $Li^7(p,\alpha)$ interaction is especially well adapted for this experiment because of the large amount of energy released.

The experimental procedure is to bombard a Li^7 target with a proton beam from the accelerator and measure the particles (in the scattering chamber) emitted at several angles. Then, using a coincidence circuit, the angle between the two detectors for which the maximum sum total energy is emitted is to be measured. Before coming to class the following is to be done: using the latest values of atomic weights available, write out the $Li^7(p,\alpha)$ reaction and determine the Q-value for a 300 KV proton beam.

Consult the following references:

1. Evans, R.D., The Atomic Nucleus, McGraw-Hill Book Co. (Latest edition available in physics office.)
2. Treado, P. A., and Lambert, J. M., American Journal of Physics, vol. 36, no. 11 (1968).
3. Duggan, J. L., American Journal of Physics, vol. 33, no. 312 (1965).
4. Bygrove, W., A Van de Graaff Nuclear Physics Laboratory Using a 400 KV Accelerator, published by High Voltage

Engineering Corporation, Burlington, Massachusetts. (Reference copy is available in the physics office.)

Your report is to include the following:

1. Schematic (block diagram) of the equipment used in the coincidence counting.

2. A mathematical analysis of the bombarding reaction. (Reaction kinematics.)

3. A comparison of the Q-values with accepted values as found in the references. (Do not forget energy losses in copper foil in front of the detectors.)

4. Graph the total energy as a function of the angle between the detectors (only the critical portion).

Explain your results. How would a reduction of beam energy affect the values?

EXPERIMENT NO. 19

A MEASURE OF THE MEAN LIFE OF NEUTRONS IN WATER

(NON-MULTIPLYING MEDIUM)

This will be the first of the pulsed experiments to be done with the sub-critical reactor and the accelerator. Deuterons will be accelerated and allowed to fall upon a tritium target for the production of fast neutrons. The generator will be pulsed in such a manner so that the neutron intensity will have completely decayed before the next burst enters the tank. At the start of the pulse the time sequence analyzer will be triggered and the intensity decay recorded as the analyzer sweeps through the set number of channels.

The procedure must of course be repeated many times in order that reliable data may be obtained. In this case the pulsing will be at 300 per second, 50 μ seconds wide, with a total sweep time of 2500 μ seconds over 20 useful channels.

From the experiment on the steady state flux distribution, determine the exponential range for both the build-up and decay portions of the curve. How can a correction for the diffusion coefficient be made? (Only the portion of the decay curve is considered which is exponential.)

References: (general)

1. Glower, D. G., Experimental Reactor Analysis and Radiation Measurements, McGraw-Hill Book Co., 1965.

2. Glasstone, S., and Sesonske, A., Nuclear Reactor Engineering, Van Nostrand Co., 1962.

3. Hoag, B., Nuclear Reactor Experiments, Van Nostrand Co., 1958.

4. Valente, A Manual of Experiments in Reactor Physics, Macmillan Book Co., 1963.

References: (specific)

5. Manley, J. H., Haworth, J., and Luebue, E. A., Physics Review, vol. 61, no. 152 (1942).

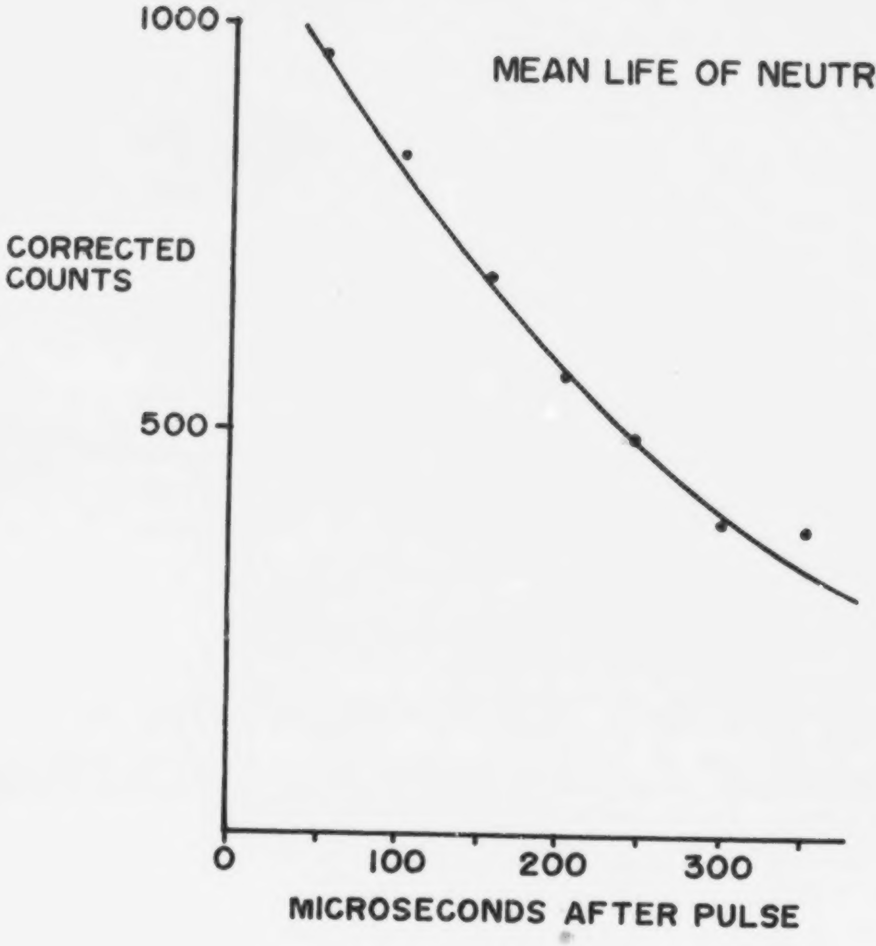
6. Megler, R., O'Brien, H., and Freed, D., Nuclear Science and Engineering, vol. 12, no. 1 (1962).

Your report is to include:

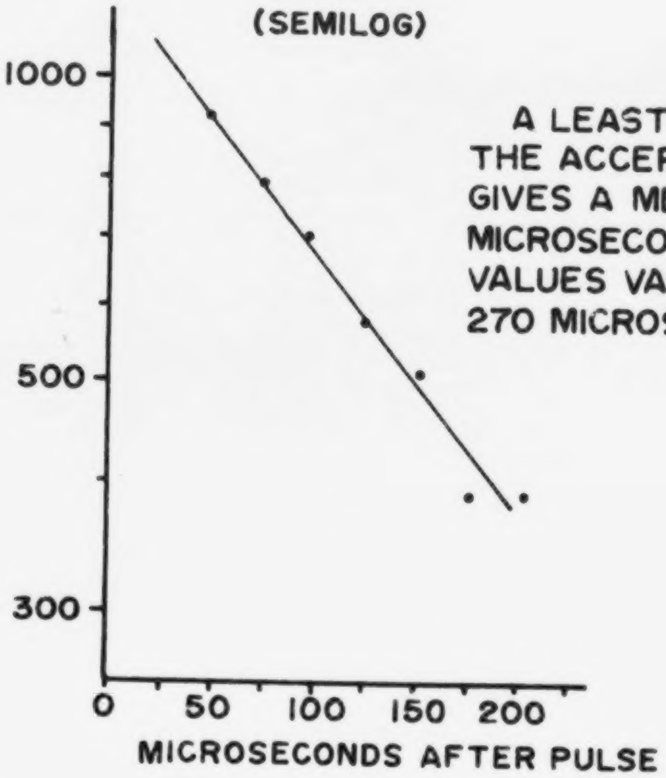
1. Graph of the neutron decay on both linear and semilog paper.

2. The calculations for mean life decay. Comparison with accepted values.

3. Discussion of how corrections are made for the coefficient of diffusion.



MEAN LIFE OF NEUTRONS IN WATER



A LEAST SQUARES FIT OF THE ACCEPTABLE VALUES GIVES A MEAN LIFE OF 216 MICROSECONDS. REPORTED VALUES VARY FROM 180 TO 270 MICROSECONDS.

SUMMARY

While the initial cost to the small school may seem rather high, the educational value of the low energy accelerator is well worth the investment. Students begin to get a real feel for research and almost all of our students taking this course continue on to graduate studies. The feeling that here is some equipment where, as one of the students said, "We finally can do something," is mighty important. The enthusiasm seems also to be catching. Since our program has been in operation, the chemistry department has asked for time to do activation analysis studies. They are also considering some studies on crystal structure. Furthermore, the biology department's interest in radiobiology has been stimulated. All in all, it is a "good shot in the arm" for any small undergraduate department.

BIBLIOGRAPHY

1. Duggan, Jerome L., "A Scattering Chamber Experiment for the Modern Physics Laboratory," American Journal of Physics, vol. 33, no. 4, 312-318 (April, 1965).
2. Hoag, J. B., and Korff, S. A., Electron and Nuclear Physics, D. Van Nostrand, Inc., 1952.
3. Melissinos, A. C., Experiments in Modern Physics, Academic Press, 1966.
4. Bleuler, E., and Goldsmith, G. J., Experimental Nucleonics, Rinehart & Company, Inc., 1952.
5. Overman, R. T., Laboratory Manual A, obtainable from ORTEC, 1967.
6. Duggan, J. L., editor, Proceedings of the Conference on the Use of Small Accelerators for Teaching and Research, available from United States Department of Commerce, Springfield, Virginia 22151, 1968. (This is an excellent summary containing many references.)
7. Duggan, J. L., Adams, W., Scroggs, R. J., and Anthony, L. S., "Charged Particle Detector Experiments for the Modern Physics Laboratory", American Journal of Physics, vol. 35, no. 7, 1967.
8. Glower, D., Experimental Reactor Analysis and Radiation Measurements, McGraw-Hill Book Co., 1965.
9. Price, W. J., Nuclear Radiation Detection, McGraw-Hill Book Co., 1964.

10. Sturm, W., editor, Reactor Laboratory Experiments, ANL-6410, Reactor Technology (TID-4300, 16th edition).

11. Marion, J. B., and Van Potter, D. M., Nuclear Research with Low Energy Accelerators, Academic Press, 1967.

Acknowledgements: to Miss Jo Ann Sumner for coming after hours to type this paper.

FAST NEUTRON PHYSICS AND THERMONUCLEAR RESEARCH

Chieh Ho and Michael Stamatelatos

Columbia University

In the process of selecting a topic for this morning's discussion, two points inevitably came to mind. First was the realization of the fact that this conference is sponsored by the American Nuclear Society, which has as one of its primary objectives the promotion and development of nuclear energy and applied nuclear sciences; second, throughout the history of research in the physical sciences the realization of solutions, at least in some areas, has been assisted and sometimes stimulated by the demands for immediate applications. Furthermore, the necessity of immediate applications often strengthens one's position when soliciting funds. Therefore, the brief talk which we shall present this morning will attempt to relate fast neutron (especially 14 MeV neutron) physics to an anticipated application which, being still in the early stages of development and research, has not yet been widely discussed.

In one of the most ambitious projects ever undertaken by mankind to overcome natural limitations, the fusion research program was started some fifteen years ago to find a new source of energy and power which could run for a very long time, indeed. This search is based upon warnings, issued by power and resource experts, that economical energy supplies may disappear after a few generations if the present trend of energy consumption on earth continues.

One of the most reliable sources of energy enjoyed by mankind from the beginning, and upon which we may continue to be dependent for the next few million years, is the energy from the sun. From various astrophysical findings, the reaction mechanisms which are taking place in the interior of the sun, are reasonably well known. In a future fusion system which will supposedly simulate a similar solar energy source on an earth scale, the following principle reactions occur:

Table 1. Principle Fusion Reactions

$$D + D \rightarrow He^3\ (0.8\ MeV) + n\ (2.5\ MeV)$$

$$D + D \rightarrow T\ (1.0\ MeV) + p\ (3.0\ MeV)$$

$$D + T \rightarrow He^4\ (3.5\ MeV) + n\ (14.1\ MeV)$$

$$D + He^3 \rightarrow He^4\ (3.6\ MeV) + p\ (14.7\ MeV)$$

$$T + T \rightarrow He^4\ (3.8\ MeV) + 2n\ (7.6\ MeV)$$

$$He^3 + He^3 \rightarrow He^4\ (4.3\ MeV) + 2p\ (8.5\ MeV)$$

$$Li^6 + D \rightarrow 2He^4\ (22.4\ MeV)$$

$$Li^7 + p \rightarrow 2He^4\ (17.3\ MeV)$$

It can be seen very easily that the D-D and D-T reactions in Table 1 are the same reactions which we use in small accelerators for the production of 2.5 and 14.1 MeV neutron beams. Therefore, the connection between thermonuclear research and the research with small accelerator-produced fast neutron beams is not hard to find.

Without wasting too much time, a brief account of a fusion system can be given as follows: A gas, or a mixture of gasses of low-Z elements, is enclosed in a container and energy is added. When the kinetic energy of the gas exceeds the ionization potential or potentials, ionization takes place. We now have a mixture of ions, electrons, and perhaps some neutrals, which is called a plasma. To prevent the charged particle constituents of a plasma from interacting with foreign nuclei, a magnetic scheme is used for containment in addition to a physical container. If everything works well according to this simple principle, there should be no problem at all. But the fact is that the stable confinement of a plasma for a time period shorter than a minute has become one of the toughest problems with which man has ever engaged. Fortunately, however, this very complex problem is not the subject of this conference. Therefore, we are very glad to leave it at this point.

Suppose the confinement of a plasma can be achieved in the next couple of decades, as is claimed by some responsible people in the thermonuclear programs. The need then for accurate fast neutron understanding will become very real. As a matter of fact, there are already small groups of researchers who are engaging in work requiring just such information. A plasma consisting of deuteron and tritium requires a kinetic temperature of 100 KeV or higher for self-sustaining reactions. The reaction rates for the D-D and the D-T reactions can be estimated by the following equations:

$$\left.\begin{aligned} R_{DD} &= \frac{1}{2} n_D^2 <\sigma v> \\ R_{DT} &= n_D n_T \ <\sigma v> \end{aligned}\right. \quad \text{reactions/cm}^3\text{/sec}$$

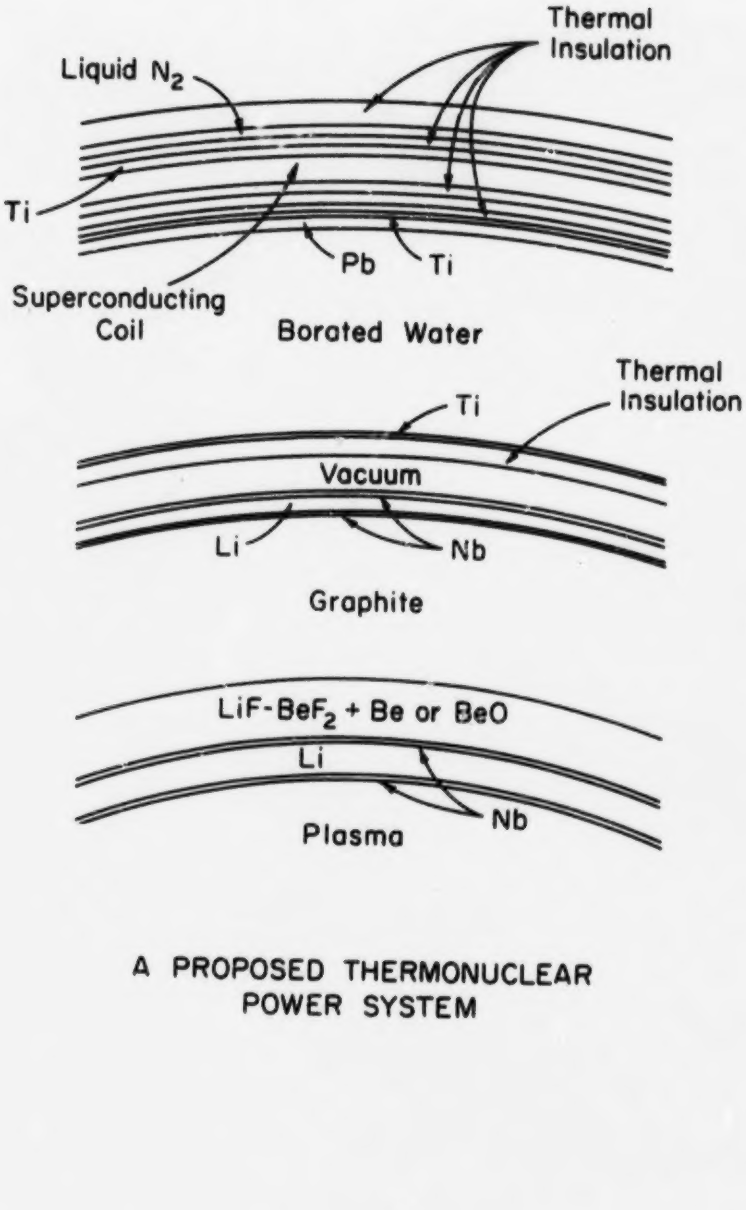
where the n_D and n_T are the densities of two species, and the $<\sigma v>$ represent the reaction probabilities of these reactions. At a kinetic temperature of 100 KeV or higher, the yield of 14 MeV neutrons can be expected to exceed 10^{13} depending upon the parameters characteristic to a particular configuration.

Figure 1 shows a conceptual layout of a future thermonuclear system(1). The central region is a vacuum region before the injection of gases into the chamber. The immediate walls of the chamber are cooled by liquid lithium which serves the dual purpose of tritium breeding. The bulk of the energy from the plasma will be absorbed in the inner high temperature region of the reflector enclosed by the niobium shell. Surrounding the high temperature region will be a water and lead shield which will shield the superconducting magnet from high temperature radiation. The water is borated to absorb thermalized neutrons. In other suggested concepts, U-238 and Th-232 layers are inserted in this region to serve the purposes of shielding against gamma radiation as well as of breeding of Pu-239 and U-233 as in a fast reactor.

Based upon the conceptual layout introduced in the previous, a summary of information and data on 14 MeV neutrons as needed in thermonuclear research is outlined below:

1. Capture interactions between 14 MeV neutrons and various nuclei
2. High energy gamma rays from capture reactions.
3. (n,2n) and (n,3n) reactions.
4. Inelastic and elastic scattering reactions of 14 MeV neutrons by various nuclei.
5. Interaction between 14 MeV neutrons and energetic protons and electrons.
6. Radiation damage to various materials by high flux 14 MeV neutrons.

These vast areas have been studied in varying degrees. However, information, when available, exists mainly in scattered form throughout the literature as reported by the various investigators. To gather it into a unified account would require work far beyond the limitations


Thermal Insulation
Liquid N_2
Ti
Pb
Ti
Superconducting Coil
Borated Water
Thermal Insulation
Ti
Vacuum
Li
Nb
Graphite
LiF-BeF_2 + Be or BeO
Li
Nb
Plasma

A PROPOSED THERMONUCLEAR
POWER SYSTEM

Fig. 1

of this conference. We, therefore, have chosen to restrict ourselves to a modest and brief survey of only two areas, namely, high energy neutron capture and (n,2n) reactions.

Fast Neutron Capture Reactions in Heavy Nuclei

Introduction. While the thermal neutron capture has been studied quite extensively, one cannot say the same about the fast neutron capture. In spite of its importance, fast neutron capture data is quite scarce. A reasonable amount of work has been done on gamma rays from fast neutron inelastic scattering but most of this research is concerned with gamma rays not exceeding a few MeVs. The reason for this lack of data is due to the considerable experimental difficulty in measuring fast neutron capture spectra and cross-sections. Some of these difficulties are:

(1) Out of the important spectrometry detectors, Ge(li) detectors are easily destroyed by high fast neutron fluxes while scintillation detectors are sensitive to both gamma rays and neutrons.

(2) Fast neutrons are very difficult to shield against and shielding brings about the creation of fast neutron capture gammas in the shielding materials.

(3) The neutron background and the gamma ray background produced by neutron interactions with the shielding material and the surrounding materials is time dependent and therefore very difficult to reproduce exactly.

(4) Some important scintillators like Nal, Csl become activated by the high neutron fluxes and in order to reproduce the activity correctly,

long runs, until the saturation activity of iodine is achieved, must be taken.

(5) Fast neutron capture cross-sections are very low, of the order of a few millibarns, so that even cosmic radiation becomes so important at these levels that it must be shielded against.

(6) High neutron fluxes, required for collecting meaningful data in reasonable time intervals, produce pile-up in the anode of the scintillation detector photomultipliers.

(7) Most of the gammas produced by fast neutrons result from inelastic scattering processes and they too can cause pile-up thus overshadowing the much less numerous primary fast neutron capture gammas (inelastic scattering gammas dominate the spectra).

Theory. The lack of experimental data has hindered theoretical physicists from obtaining a definitive theoretical model of the fast neutron capture reactions. There are, however, proposed mechanisms believed to be true depending upon the neutron energy at which the capture occurs. The oldest models are the compound nucleus model and its more sophisticated relative, the statistical model. According to them, the interacting neutron shares its whole energy among the nucleons of the target nucleus and the resulting excited compound nucleus subsequently decays independently of its mode of formation. This decay is treated like a statistical process and statistical methods can be applied for calculating the neutron capture spectra and cross-sections. This model favors the emission of low energy gamma rays since it is improbable that many nucleons will jointly and simultaneously give up their excitation energies. By comparison with the experimental results, this model accounts fairly well for the thermal and slow neutron capture spectra.

For neutrons of energy in excess of a few MeV's however, the experimentally determined cross-sections are much larger than the ones predicted by the statistical model. Besides, a definite excess of gamma rays about 6 MeV over the amount predicted by the compound nucleus theory is observed. According to the compound nucleus theory, almost no gamma rays about 7 MeV should arise in the capture process. This considerable discrepancy with the experimental results motivated Lane and Lynn(2) to propose the direct capture method, one-stage reaction model, according to which, the incoming neutron directly enters an empty particle orbit of the target nucleus, the excitation energy being emitted in the form of a gamma ray. This capture model predicts the emission of high energy gamma rays and also higher capture cross-sections.

At about 10 MeV neutron energy, however, the direct capture mechanism predicts a capture cross-section of about 0.1 mb. which is maller than the one experimentally measured by about a factor of ten. Recently, Brown and Clement et al(3,4) have proposed a third model, the semi-direct capture model or the collective capture model. According to this model, a two-stage process takes place. The interacting neutron enters a shell model orbit of the target nucleus but the excitation energy is not simply radiated away. An intermediate, "doorway" state arises, in which the neutron is in a bound state and the target nucleus is excited by a collective oscillation to its giant dipole resonance state, provided the neutron energy is sufficiently large. The cooperative character of these collective oscillations enable the prediction of a capture cross-section larger by a factor of ten than the one given by the direct capture model, thus bringing the calculated cross-sections into agreement with the experimental ones. If the neutron energy does not allow reaching the giant dipole state, the excess energy excites a nucleon from one orbit to another, forming a two-particle-one-hole excited state. This state has the tendency to decaying by returning the second nucleon to its original orbit and emitting the excitation energy in the form of a gamma ray. This way, single particle excitations are favored. Theoretically, this mechanism can be treated, due to the detailed balance principle, the same way as the inverse, photonuclear, reaction. An idealization of this model is provided by the infinite harmonic oscillator potential. Equivalently, the process can be treated as a collective model of the dipole vibration of a proton fluid against a neutron flued(5). Thus, semi-classical results can be used. Clement et al.(4) obtained the following expression for the collective capture cross-section:

$$\sigma = \frac{\pi}{k'^2} \sum_{l'l} (2l'+1) \frac{\Gamma_\gamma \Gamma_{in}}{(\varepsilon_{l'} - \varepsilon_r)^2 + \frac{1}{4}\Gamma^2}$$

where:

$$\varepsilon_r = \varepsilon_l + \hbar\omega_1 \quad ; \quad \langle \eta_z \rangle^2 = \frac{A}{NZ} \frac{\hbar^2}{2M} \frac{1+0.8x}{\hbar\omega_1}$$

$$\Gamma_\gamma = \frac{4}{3} \left(\frac{NZ}{A} \right)^2 e^2 k_\gamma{}^3 \langle \eta_z \rangle^2$$

$$\Gamma_{in} = \frac{Mk'}{2\hbar^2} \left[\frac{NZ v_1}{A^2} \right]^2 \frac{l+l'+1}{2l'+1} \langle \eta_z \rangle^2$$

$$\times \left| \int_0^\infty dr \, u_{nl}(r) \, r^2 \frac{df(r)}{dr} \psi_{l'}(r) \right|^2$$

k' = wave number of the incident nucleon.

$\varepsilon_{\ell'}$ = center of mass energy.

ℓ' = orbital angular momentum quantum number.

$n, \ell, \varepsilon_\ell$ = principal quantum number, orbital angular momentum quantum number and excitation energy of the nucleon in the final state, respectively.

k_γ = **wave number of the emitted photon.**

$\hbar\omega_1, \Gamma$ = excitation energy and width of the giant dipole resonance of the nucleus A, N, Z

e, M = charged and reduced mass of the nucleon in the incident channel.

η_z = matrix element of the target dipole operator.

x = exchange force fraction = 1/2 (usually)

$v_1 \frac{df(r)}{dr}$ = isopin part of the optical potential

$f(r)$ = form factor of the real part of the optical potential

$u_{n,\ell}(r), \psi_{\ell'}(r)$ = the radial part of the bound-state wave function and the incident wave function, respectively.

The incident wave function are calculated with an optical potential of the form (including spin-orbit effects):

$$V(r) = -V_0 f(r) - iW_0 g(r) - (V_{s.o.})_0 \left(\frac{\hbar}{\mu c}\right)^2 \vec{\ell}\cdot\vec{\sigma}\, \frac{1}{r} \frac{df(r)}{dr}$$

where:

$$f(r) = \left[1 + \exp\left\{(r - r_{0v} A^{1/3})/a\right\}\right]^{-1}$$

$$g(r) = \exp - \left\{(r - r_{0w} A^{1/3})/b\right\}^2$$

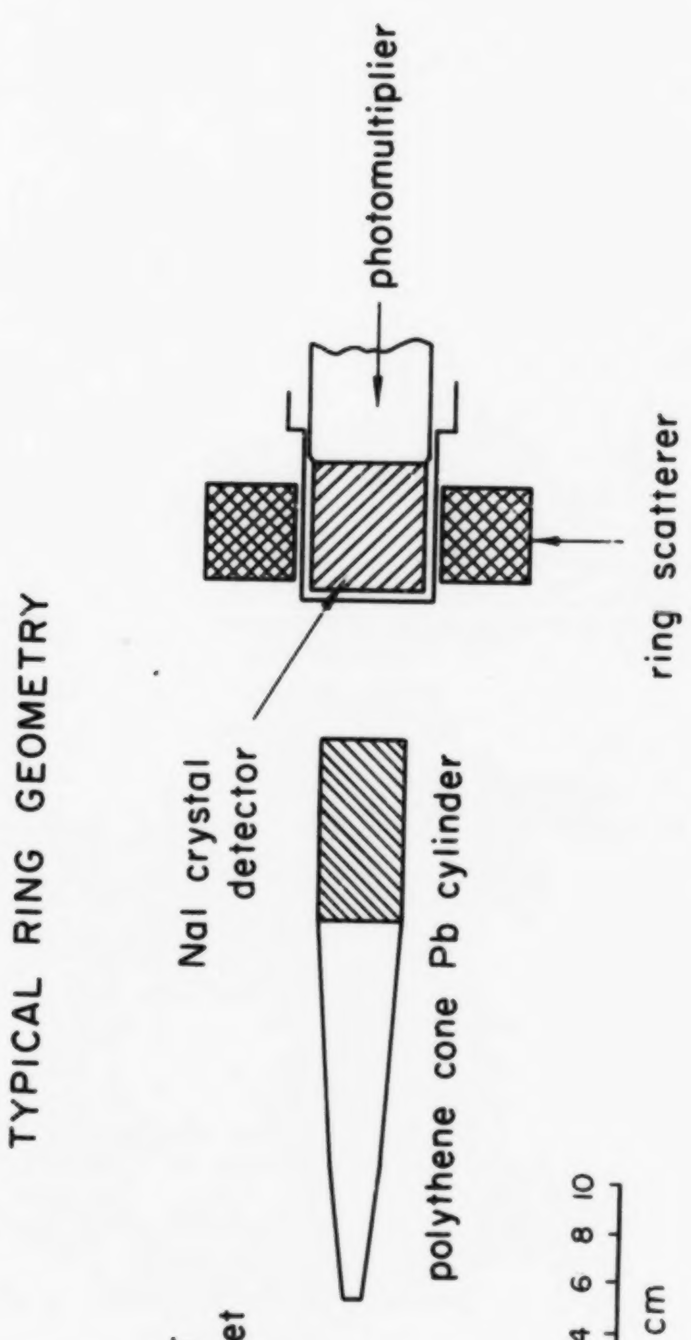
$\vec{\ell}$ = orbital angular momentum operator

$\vec{\sigma}$ = Pauli spin operator

$r_{0w} = r_{0v} = 1.25$ fm. ; $a = 0.65$ fm. ; $b = 0.98$ fm.

Experimental arrangements. There are several experimental set-ups which have been used for measuring gamma ray spectra from fast neutron captures. Some of these set-ups have been used primarily for measuring inelastic scattering gamma rays while other were used mainly for capture gammas. Since most of the set-ups include neutron shielding, the following types of materials are customarily used: first, a dense material (lead or steel) in the form of a wedge between the neutron source and the detector to initially slow down 14 MeV neutrons, mainly by inelastic scattering; then follows a good slow neutron absorber which, however, must not give rise to high energy gamma rays (boron, lithum); finally, a very dense material, usually lead, to attenuate the gamma radiation produced by the capture of neutrons in the slow neutron absorbing shield or elsewhere outside the sample.

One of the oldest experimental arrangements used is the "ring geometry", in which the sample is in the shape of a ring surrounding the gamma ray detector (figure 2). For this arrangement, the background arises chiefly from either I-128 activity formed in the NaI (Tℓ) scintillator by the activation of iodine, or by inelastic scattering and capture of neutrons in Na or I. The first background can be standardized and subsequently subtracted if long runs are taken until the I-128 concentration reaches equilibrium. The second one can be determined if the studied sample is replaced by a sample giving the same amount of scattering and a low intensity, smooth, well-known gamma ray spectrum. This is difficult to achieve at high neutron bombarding energies)above a few MeV's).



TYPICAL RING GEOMETRY

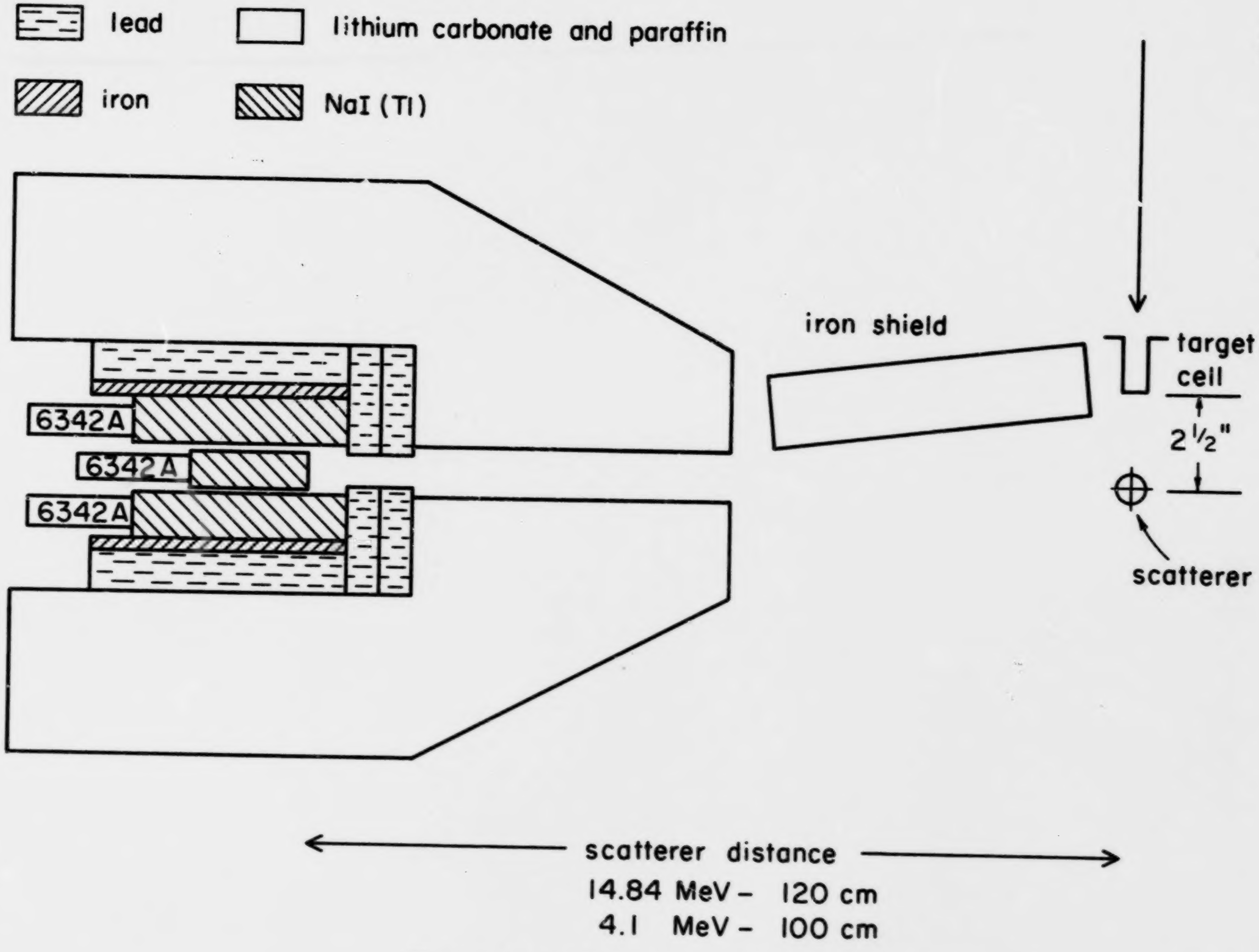
photomultiplier
ring scatterer
NaI crystal detector
polythene cone Pb cylinder
Ti T target
proton beam
0 2 4 6 8 10
cm

Fig. 2

Another arrangement is the one first used by Trail and Raboy$^{(6)}$ and subsequently used quite extensively by a group of researchers at the Texas Nuclear Corporation, Austin, Texas. (figure 3). This detector consists of a large annular NaI scintillation detector placed in anticoincidence with the central cylindrical NaI crystal. The purpose of this arrangement is to eliminate from analysis all gamma rays which have not dissipated their full energy in the central scintillator. In this way, Compton scattering gammas and even cosmic radiation are eliminated. The elimination of the Compton gamma rays helps improve the detector resolution. The shielding and also the use of a pulsed beam help keep the neutron background reasonably low. A third set-up consists of a single NaI (Tl) detector with adequate neutron shielding and also employes the time-of-flight method of discriminating between the neutrons and the gammas. This type of detector has been extensively used by researchers at Studsvik, Sweden$^{(7)}$. (figure 4) In this arrangement, shielding is provided only against direct target neutrons. Gibbons et al.$^{(8,9)}$ used a similar detector in which, however, there also exists shielding against sample scattered neutrons. (figure 5) Another very similar detector was used by Engesser and Thompson at the U. S. National Radiological Defense Laboratories in San Francisco, California$^{(10)}$.

Another detector used for gamma ray spectrometry is the three-crystal-pair spectrometer. As shown in figure 6, it was not used for measuring fast neutron capture spectra. If used for this purpose, it would have to have the adequate neutron and gamma ray shielding as mentioned before.

The three-crystal-pair spectrometer analyzes only gamma rays which deposit their full energy in the central NaI scintillator. This is done


lead
lithium carbonate and paraffin
iron
NaI (Tl)
6342A
6342A
6342A
iron shield
target cell
2 1/2"
scatterer
scatterer distance
14.84 MeV - 120 cm
4.1 MeV - 100 cm

Experimental Geometry Not to Scale

Fig. 3

STUDSVIK DETECTOR

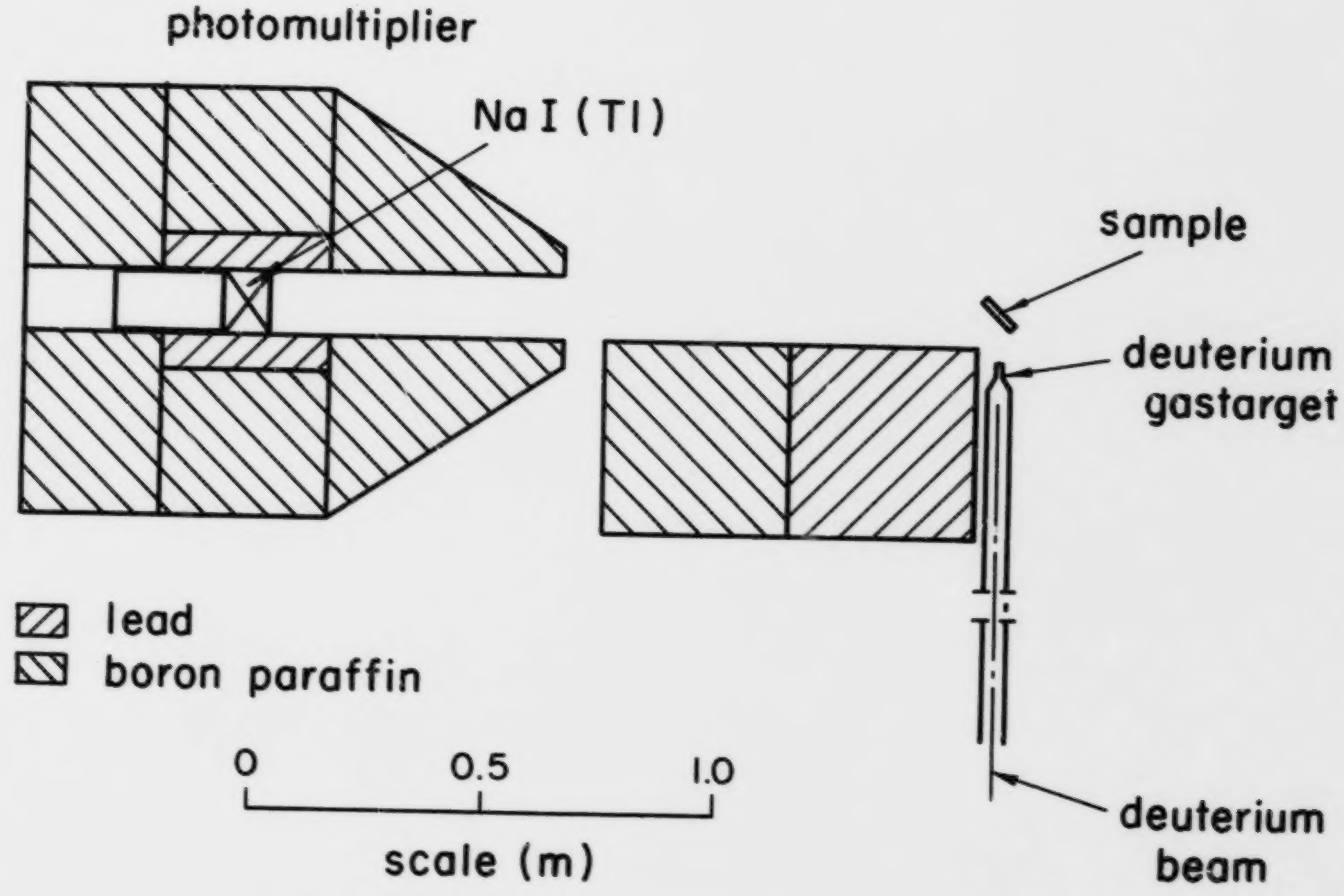

photomultiplier
Na I (Tl)
sample
deuterium gastarget
deuterium beam
▨ lead
▧ boron paraffin
0
0.5
1.0
scale (m)

Fig. 4

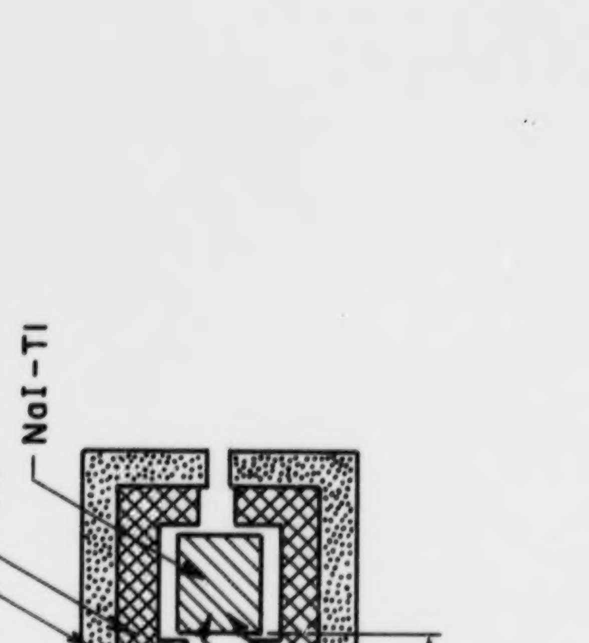

Li^6-(CH$_2$)$_n$
Pb
NaI-Tl
30cm
θ
n's
15 → 50cm
≥ 4n's;
I$_p$ ~ ima
≤ 1 Mc/sec
p's

Fig. 5

THREE-CRYSTAL-PAIR SPECTROMETER

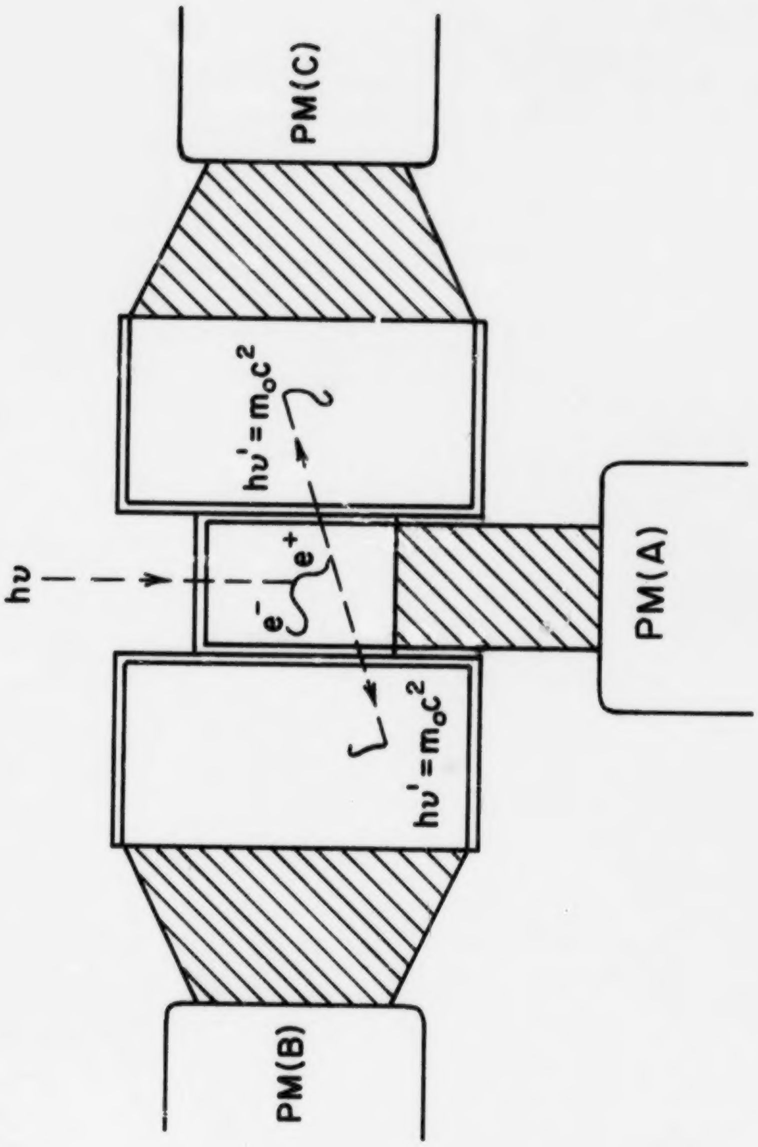
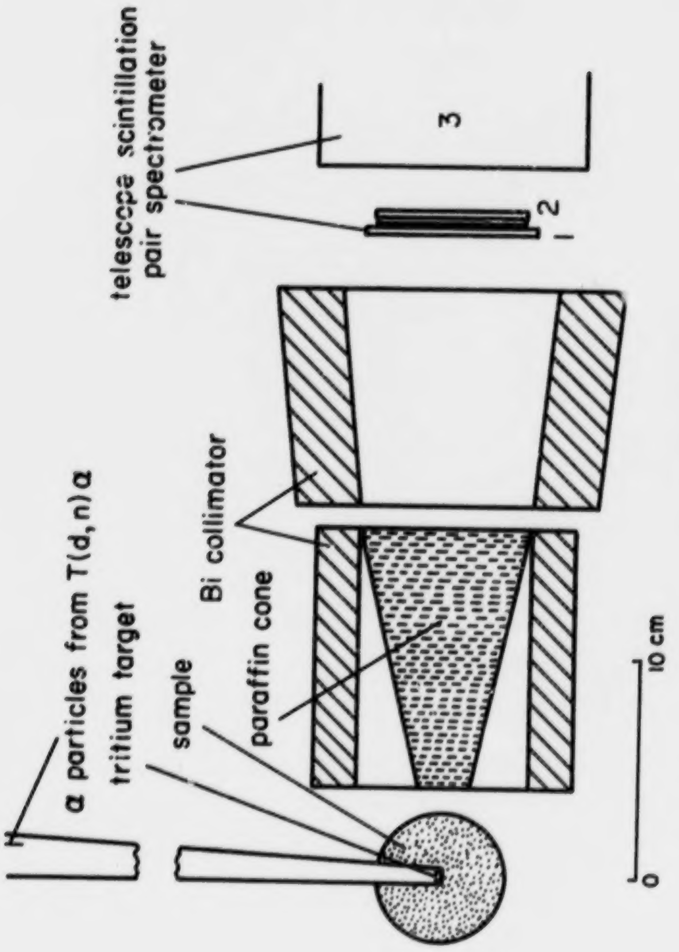

PM(C)
PM(A)
PM(B)
hυ
e^-
e^+
$h\upsilon' = m_oc^2$
$h\upsilon' = m_oc^2$

Fig. 6

by examining only pair production events, i.e. events detected in the central crystal which occur in coincidence with the 512 KeV annihilation peaks in the two adjacent scintillators. Here, again, time-of-flight may be employed in order to reduce the neutron background.

The telescrope-pair spectrometer(12) was specially designed for measuring high energy gamma ray spectra following fast neutron capture events (figure 7).

Unlike the previously described detectors, this spectrometer, as designed by Cvelbar et al., uses plastic (NE 102A) scintillators which have the advantage of not becoming activated and also permitting discrimination against sample scattered neutrons. This spectrometer is sensitive to higher energy gammas (from about 5 MeV up). Since it is not very efficient, overall, a 4π sample geometry becomes almost mandatory. The spectrometer is composed of three plastic NE 102A scintillators labeled 1, 2 and 3 in fig. 7) and a thin lead converter. The first two scintillators are small (3" x 1/8") disks acting as dE/dx detectors while the third one is a 5" x 5" cylinder. The purpose of the lead converter is to create positron-electron pairs since the plastic scintillators, being composed of light elements, are not too sensitive to gamma rays but are very sensitive to electrons. Besides, the fact that only pair events are detected, insures that only gamma rays which lose their entire energy in the large detector are detected. In this way, one obtains a good resolution with plastic scintillators which, in fact, exhibit fairly poor resolution for gamma radiation. The capture data is collected from the large detector whose signal is gated with the coincidence with No. 2 and the anticoincidence with No. 1. By setting No. 1 in anticoincidence with No. 3, one insures that only events originating in the converter are analyzed. Thus, by proper discriminator setting, neutrons are


α particles from T(d,n)α
tritium target
sample
paraffin cone
Bi collimator
telescope scintillation
pair spectrometer
1
2
3
0
10 cm

TELESCOPE-PAIR SPECTROMETER

Fig. 7

eliminated.. No. 2 is set so that it examines only pair events. This is done in the following way; since No. 2 is a dE/dx detector, high energy electrons deposit in it an almost constant amount of energy, i.e. independent of the electron energy. Thus, if one biases against the energy deposited by one electron or less and against energy deposited by more than two electrons (corresponding to the electron-positron pair), the coincidence of No. 2 and 3 insures that only pair events are analyzed. Thus, Compton electrons are eliminated. As a bonus, neutrons are also pretty much eliminated, due to the narrow window setting in No. 2. With this arrangement, one manages to reduce the background (neutron background included) to a negligible level. In this respect, this arrangement is worth considering as an alternate to the time-of-flight technique. Besides, the fact that the pair production cross-section increases with energy makes this spectrometer more sensitive to the high energy capture gammas than to the far more numerous inelastic scattering gammas. This is a desirable feature when one is interested in capture gammas only.

A detector used for measuring neutron capture cross-section is shown in figure 8 (13) and was employed by Diven, Terrel and Hemmendinger at the Los Alamos Scientific Laboratory for measuring capture-to-fission ratios for fast neutrons [T(p, n)] in U^{235}.

The hollow cylindrical liquid scintillator surrounding the sample provided an almost 4π detector. A pulsed beam was used in order to eliminate a slower second group of neutrons always present in the T(p, n) reaction.

An alternate simple set-up which we propose for the purpose of measuring fast neutron capture and inelastic scattering cross-section is shown in figure 9. Since NE 213 can discriminate against neutrons by pulse shape discrimination, the anticoincidence between the large plastic

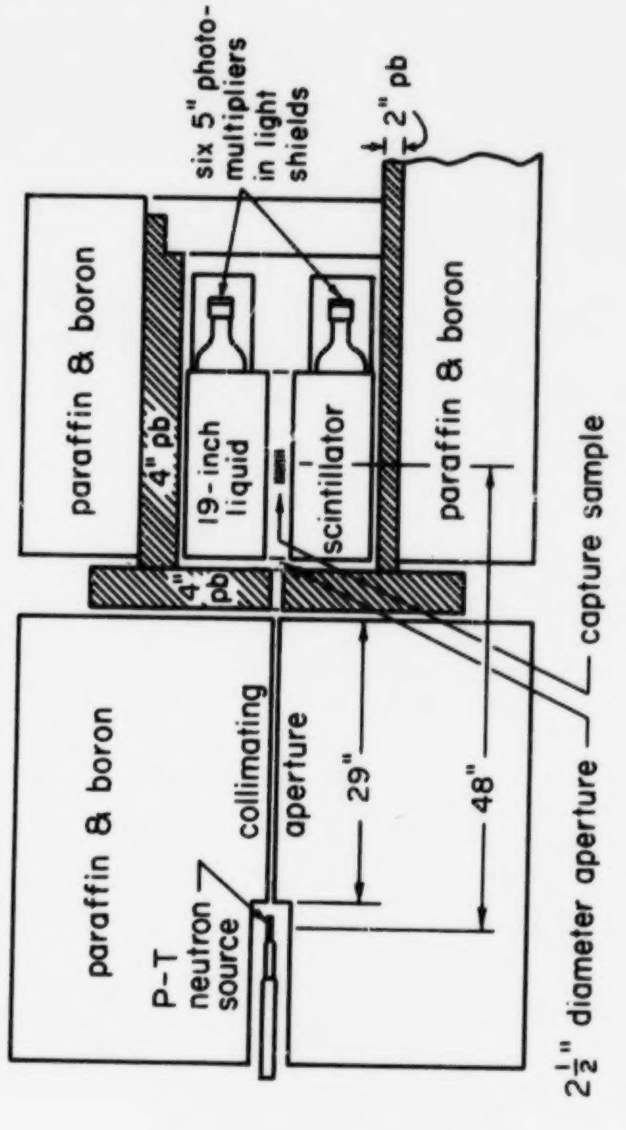
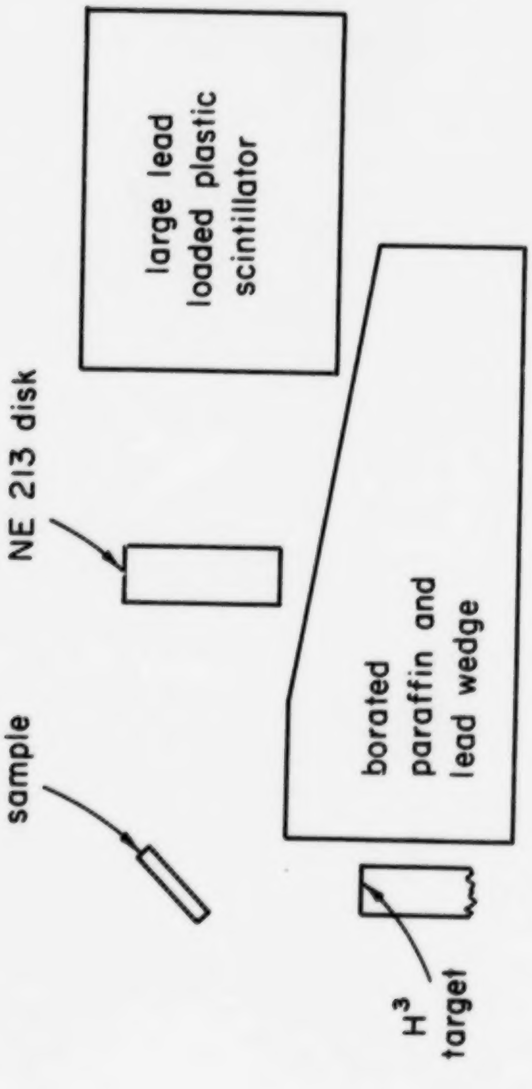

paraffin & boron
P-T
neutron
source
collimating
aperture
29"
48"
2½" diameter aperture
4" pb
4" pb
paraffin & boron
19-inch
liquid
scintillator
capture sample
paraffin & boron
six 5" photo-
multipliers
in light
shields
2" pb

Fig. 8


large lead
loaded plastic
scintillator
NE 213 disk
sample
borated
paraffin and
lead wedge
H^3
target

CAPTURE CROSS-SECTION MEASURING ARRANGEMENT

Fig. 9

scintillator and the NE 213 disk properly set to analyze only the scattered neutrons (by the sample or elsewhere) enables measuring gamma ray production cross-section in the sample. The lead loading of the plastic scintillator gives the crystal an increased sensitivity to gamma rays.

In conclusion, comparisons between the calculated and measured fast neutron capture gamma ray spectra lead to the strong belief that the semi-direct or collective capture process is the main one responsible for the behavior of fast neutron capture cross-sections. However, due to lack in accurate data, the field is still open to discussion. Figure No.10 shows a comparison of the experimental data as obtained by Cvelbar et al.(12) with the calculated cross-sections by using the various capture theories.

(n,2n) Cross-Section Measurements

Methods. Due to the obvious difficulty in distinguishing (n,2n) neutrons from (n,n') neutrons, hardly any data exists on (n,2n) neutron spectra. Instead of measuring spectra, experimentalists have concentrated on measuring (n,2n) cross-sections. Until about ten years ago, the almost exclusive method of measuring (n,2n) cross-sections was through the measurement of the activity induced by the (n,2n) reaction on the target nucleus. This method was, of course, good only in cases where the residual nucleus was radioactive(14). The favorite elements were those for which the (n,2n) activation products had short half-lives and particularly those which were $\beta+$ emitters. The reason for the latter is that $\beta+$ emitters can be very accurately determined through the coincidence measurement of their annihilation gamma radiation. As a matter of fact, some (n,2n) reactions giving such $\beta+$ emitters were so well

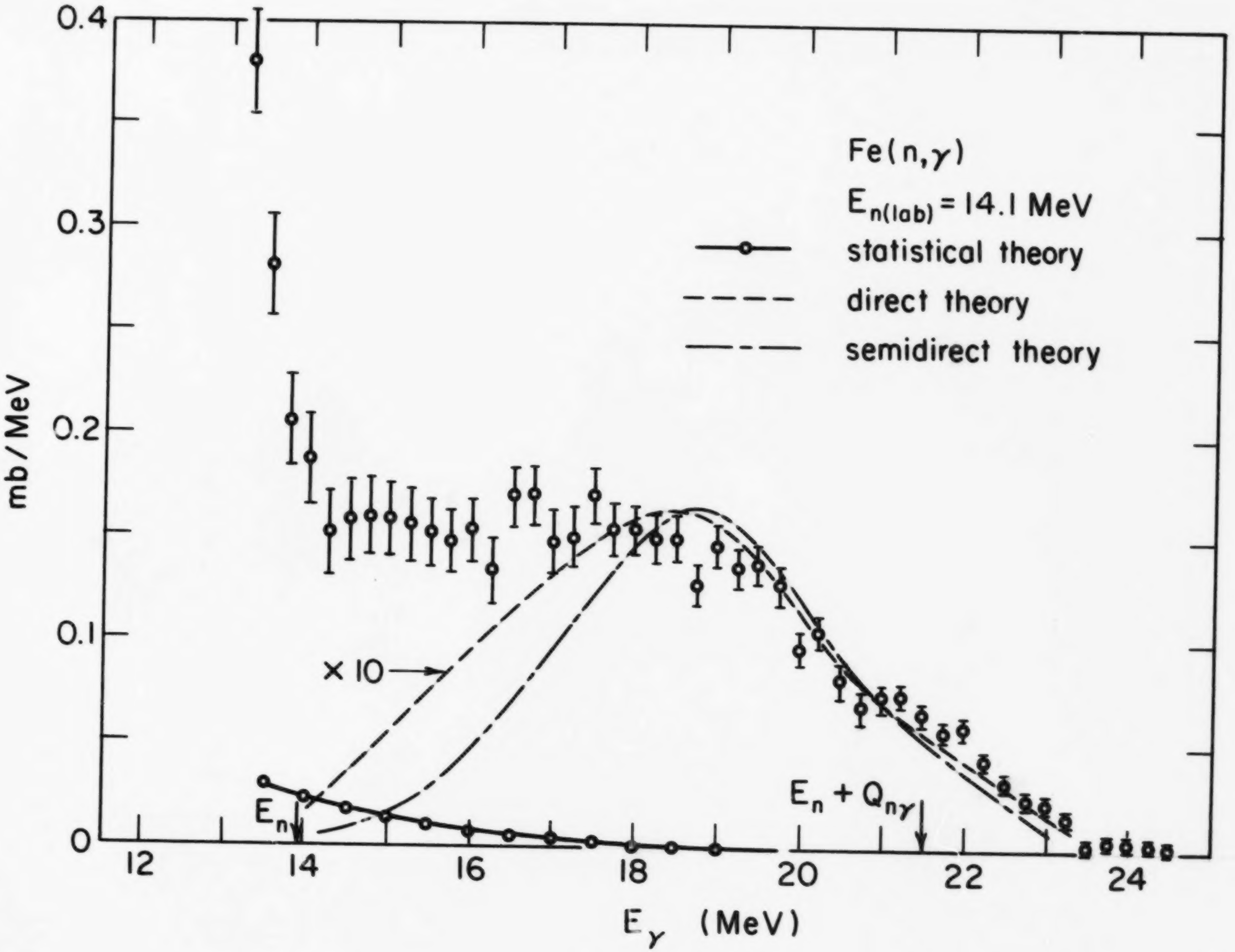

Fe(n,γ)
E_n(lab) = 14.1 MeV
statistical theory
direct theory
semidirect theory
mb/MeV
0.4
0.3
0.2
0.1
0
12
14
16
18
20
22
24
E_γ (MeV)
× 10
E_n
E_n + Q_nγ

Fig. 10

studied and their cross-sections so accurately measured that they became very useful for the reverse procedure, i.e., determining the neutron flux given the (n,2n) reaction cross-section. Out of these "threshold" neutron detectors, the ones which are important at 14 MeV incident neutron energy are shown in Table 2. (listed are only those isotopes for which the (n,2n) reaction leads to aproduct with a half-life less than one hour).

Table 2.

Isotope	Abundance	Half-life (min.)	Lowest Energy of Use (MeV)	(n,2n) at 14 MeV
Pr-141	100	3.4	9.4	2.08 b.
Sm-144	3.16	8.3	9.6	1.2 b.
N-14	99.63	10	10.6	5.7 mb.
Cu-63	69.1	9.73	10.65	0.55 b.
Zn-64	48.89	38.3	11.8	0.167 b.
Cl-35	75.4	32.4	12.6	3.5 mb.
K-39	93.08	7.7	13.1	4.0 mb.
Cr-50	4.31	41.8	13.4	27 mb.

Since this activation method certainly does not work if the reaction product is not radioactive, other methods must be employed in these cases. Particularly interesting in this respect is the case of Be-9 for which the (n,2n) reaction gives no residual radioactivity. Therefore, Be-9 became a very popular candidate for alternate cross-section measurement methods. One such alternate method consists of a 4π-type detector which, in one case for example, was a large cadmium loaded liquid scintillator(15) (containing toluene, terphernyl, α-npo, cadmium propionate and methanol) or, in another case, an aquecs solution of potassium permanganate(16).

In the first set-up developed at Los Alamos by Ashby, Catron, Newkirk and Taylor, a collimated burst of 14.1 MeV neutrons passed through a six-inch diameter axial tube into a 200 gallon liquid scintillator tank, 40 inches long and 40 inches in diameter. The target of the investigated element was a cylinder centrally located in this tube. The neutrons, slowed down in the liquid, gave rise to capture gammas in cadmium and the (n,2n) events were measured by detecting in the scintillator two gamma ray pulses occuring within 25 microseconds following the arrival of the neutron burst at the target in the center of the scintillator. The coincidence started 0.5 microsecond after the last neutrons from the burst had arrived at the scintillator in order to assure that prompt gamma rays from the target, or recoil protons from slowing down of the neutrons in the scintillator, would not be counted. The cadmium loading was such that most of the neutrons were captured within 25 microseconds. The elements studied were: D, Be, C, N, F, Fe, Cu, Ag, Ta, Au, Rb, Bi. The values of the cross-sections were obtained from the expression:

$$\sigma\ (n,2n) = \frac{4\pi}{A \times 10^{-24}} \quad \frac{A.W.}{M} \times \frac{L^2}{Y} \times \frac{K2}{\alpha} \times \frac{1}{\varepsilon^2}$$

where

A = Avogadro's number

A.W. = atomic weight of the target material

M = mass of the target

L = distance from neutron source to target

Y = neutron production per alpha count
(the neutron flux was determined by counting the alpha particles from the D-T reaction)

ε = efficiency of the detector

$\frac{K2}{\alpha}$ = net double pulses per alpha count (calculated in order to correct for accidental double pulses)

The second mentioned 4π detector was developed by Fischer and was exclusively used for measuring the (n,2n) cross-section of Be-9. The D-D neutron beam was collected through either one of four collimated ports tilted at angles of 0°, 54°, 74° and 88° with respect to the deuteron beam direction in order to obtain 3.19, 2.92, 2.96 and 2.57 MeV neutrons respectively. The selected beam was passed through the axis of the beam tube of a 125 liter activation chamber containing permanganate solution. Neutrons first slowed down in water, were partly (14%) captured by manganese nuclei (13.2 barn thermal neutron capture cross section) giving rise to Mn-56 beta activity (2.59 - hour half-life), and partly by the hydrogen in water. Upon capturing a neutron, the activated manganese atom emitted a gamma ray and recoiled with sufficient momentum to separate from the permanganate ion, thus resulting in an insoluble MnO_2 molecule which was obtained by the fast oxidation of manganese. The MnO_2 crystals were filtered out of the solution and placed between two NaI(Tℓ) detectors. The 0.845 MeV gamma activity following the beta decay of manganese gave a measure of the number of neutrons given by the sample. In order to eliminate the background activity produced by neutrons leaking in from the room, and also the neutrons elastically scattered by the sample, three separate irradiations were made for each (n,2n) cross-section determination by using three identical potassium permanganate wolutions each time. The first irradiation was used for background determination and was performed with no neutron target in the beam tube. The second one, which meant to simulate the pure scattering events, was done using a carbon target of the same size as the beryllium target. Finally, the third activation was performed with a beryllium target, essentially opaque, to the incident neutron beam. The (n,2n) cross-section was obtained from the comparison of these three independent runs. Possible multiple scatterings of the neutrons in the target were also taken into consideration.

Another method of detecting (n,2n) events and hence measuring (n,2n) cross-sections is the so-called "sphere multiplication" method.(17) This method is based on the observations that out of the neutron induced reactions, some (capture, (n,p), (n,d), etc.) result in the reduction of the total number of neutrons while the (n,2n) reaction results in the increase in the total number of neutrons, (neutron multiplication). Yet some other reactions (elastic scattering, inelastic scattering) leave the number of neutrons unchanged. Thus a balance of the total number of neutrons can be set up and the neutron multiplication of a layer of material, defined as the total number of neutrons emerging divided by the number of primary neutrons incident upon the layer, can be measured and the (n,2n) cross-section subsequently calculated. Consider a thin spherical shell of material surrounding an isotropic 14-MeV neutron source. One can establish a relationship between the multiplication, M, and the transmission, T, of the primary energy neutrons (for non-fissionable materials) :

$$M = T + (1-T)\left\{\frac{\sigma_{is} + 2\sigma_{n,2n} + 3\sigma_{n,3n}}{\sigma_i}\right\}$$

where

T = the fraction of the source neutrons which emerge from the shell having suffered no inelastic collision

σ_i = inelastic collision cross-section

$= \sigma_{total} - \sigma_{elastic}$

$= \sigma_{is} + \sigma_{n,2n} + \sigma_{n,3n} + \sigma_c$

σ_{is} = inelastic scattering cross-section i.e. any (n,1n) inelastic reaction

$\sigma_c = \sigma_{n,p} + \sigma_{n,\alpha} + \sigma_{n,\gamma}$ etc.

= the sum of all cross-sections for all processes resulting in the disappearance of a neutron.

Rearranging the above equation, one obtains the number of neutrons per inelastic collision:

$$\frac{M-T}{1-T} = 1 + \frac{\sigma_{n,2n}}{\sigma_i} + 2\,\frac{\sigma_{n,3n}}{\sigma_i} - \frac{\sigma_c}{\sigma_i} \equiv 1 + k$$

The quantity M can be measured by a relatively energy-independent neutron detector, given that the number of source neutrons is known. Since the neutrons resulting from inelastic scattering of 14 MeV neutrons with intermediate and heavy nuclei are almost entirely of low energy, the neutrons emerging from the shell are in one of two energy groups: 14 MeV or below 3-4 MeV. Graves and Davis found that by using a long counter, whose efficiency is approximately energy-independent below 5 MeV, a "measured multiplication", M', can be obtained:

$$M' = T + (1-T)(1+k)\left(\frac{\varepsilon'}{\varepsilon_0}\right)$$

where

$\frac{\varepsilon'}{\varepsilon_0}$ = efficiency for detecting the inelastic neutrons divided by the efficiency for detecting the primary neutrons.

The background was measured with a thick iron shadow cone between the source and the long counter. High energy neutrons were detected with properly biased transstilbene crystal. Since, for all but the lightest elements, degradation of neutron energy by elastic scattering is negligible, the count rate of this detector, with and without the scattering sphere, gave the transmission, T. The gamma rays from neutron captures in the sphere were not significant enough to interfere except in the case of iron. The inelastic collision cross-section was obtained from the following relationship:

$$T = \exp\left[-N\sigma_i\right]$$

where

$$N = \frac{\text{atoms}}{\text{cm}^2} \times 10^{-24}$$

Since

$$\left(\frac{M-T}{1-T} - 1\right)\sigma_i = k\sigma_i \equiv \sigma_{n,2n} + 2\sigma_{n,3n} - \sigma_c$$

if $\sigma_{n,3n}$ is ignored, which must be true for 14 MeV neutrons on almost all elements, then one can obtain lower and upper limits for σ_c and $\sigma_{n,2n}$:

$\sigma_c \geq 0$; $\sigma_{n,2n} \geq k\sigma_i$ corresponding

to the upper limit $\sigma_{is} \leq \sigma_i - k\sigma_i$ for σ_{is}

and

$$\sigma_c \leq \frac{1}{2}\left(\sigma_i - k\sigma_i\right) \; ; \; \sigma_{n,2n} \leq \left[k\sigma_i + \frac{1}{2}\left(\sigma_i - k\sigma_i\right)\right]$$

corresponding to the zero lower limit of σ_{is} . The elements studied were: C, Al, Fe, Cu, Zn, Ag, Cd, Sn, Au, Pb, Bi.

Various spectroscopic techniques were also used for the measurement of (n,2n) cross sections. In one fo them(18) used by Fowler, Hanna and Owen, for the cross section measurement of the $Be^9(n,2n)Be^8$ reaction, proton recoils from the neutrons coming from the sample were detected in coincidence with two large trans-stilbene scintillators. In another method(19), applied again to beryllium by Marion, Levin and Cranberg, the (n,2n) cross section was measured indirectly. It was extracted from measured values of the total, elastic, inelastic and (n,α) cross sections by subtracting from the first, the subsequent ones. A combination of time-of-flight and total-minus-elastic techniques was employed in this experiment.

Rosen and Davis(20), using a nuclear emulsion detector, measured non-elastic neutrons which they used in obtaining (n,2n) cross section by assuming that an (n,2n) process took place when the energy of the first emitted neutron was low enough to energetically permit the emission of a second one. The elements tudied were Be, Ta and Bi. The cross section, with respect to energy and angle for the emission of neutrons from the Ta and Bi samples, was determined as follows. The primary neutron flux averaged over the scatterer was:

$$F_n = \frac{F_0}{l}\int_0^l e^{-\sigma_{tr} n_0 t}\, dt = F_0\left(\frac{1-e^{-\sigma_{tr} n_0 l}}{\sigma_{tr} n_0 l}\right)$$

where

F_o = neutron flux (determined by counting the α particles from the T (d,n) He^4 reaction) incident on the cylindrical scatterer

A, ℓ = scatter area and length, respectively

n_o = number of nuclei per cm^3 in the scatterer

σ_{tr} = transport cross section at 14 MeV for the element investigated.

The differential cross-section for the emission of neutrons of energy E and angle θ was given by

$$\sigma(E,\theta) = \frac{F_n(E,\theta)\, R^2}{n_o \ell\, \overline{F}_n A}$$

where

$F_n(E,\theta)$ = number of neutrons of energy E to E + dE per unit energy emitted into $1/R^2$ steradians at a distance R from the center of the target.

The flux at the detector was calculated from:

$$F_n\,(E,\theta)\, dE = \frac{4\pi N(E,\theta)\quad dE}{\sigma_{n-p}(E)\; 4 \langle \cos\gamma \rangle_{av}\; n_p\, V_e\, \Theta\, P(r)\, A_t(E)}$$

where

$N(E,\theta)\, dE$ = number of proton recoils between E and E + dE at angle

$\sigma_{n-p}(E)$ = total n-p cross-section at energy E

$\langle \cos\gamma \rangle_{av}$ = average value of the cosine of proton scattering angle

n_p = hydrogen density in emulsion

V_e = emulsion volume analyzed

Θ = solid angle of acceptance of proton recoils

$P(r)$ = probability that a track of range r will end within the emulsion layer

$A_t(E)$ = attenuation correction for neutrons in the emulsion.

The statistical model method was used to obtain a temperature for Ta and Bi corresponding to the evaporation of the first neutron from the compound nucleus: if one assumes that two neutrons are emitted in succession and the temperature falls as the square root of the excitation energy, the neutron distribution

$$F_n(E)\,dE = E^{5/11}\,e^{-12E/11\tau_1}\,dE$$

gives τ_1 associated with the first neutron. The value of τ_1 was obtained by a least squares fit. Similarly, the value t associated with the evaporation of the second neutron was obtained by assuming the spectrum to be represented by:

$$F_n(E)\,dE = E\,e^{-E/\tau}\,dE$$

after the first neutron contribution was subtracted. Thus, values for the nonelastic cross-section ($\sigma_i = \sigma_{n,n'} + \sigma_{n,2n}$), σn, n' and σn, 2n were obtained based on the assumption that an (n,2n) reaction was realized whenever the energy of the first neutron was low enough to make the emission of the second neutron energetically possible by at least .5 MeV.

The obtained experimental data was corrected for: detection of neutrons of degraded energy from the primary beam which elastically scattered into the detector; spurious tracks from (n' charged particle) reactions in the emulsions; multiple scattering of neutrons in the sample; attenuation of the neutrons in the detector.

Data Analysis. (n,2n) reaction have long been successfully considered as evaporation processes$^{(21)}$. To date, even the most modest compound nucleus approximation has given satisfactory agreement with the often not very accurate experimental data. Unsing a two-particle statistical emission approach$^{(22)}$, Pearlstein$^{(23,24,25)}$ has calculated (n,2n) cross-section for medium-weight and heavy elements. He used a crude statistical model $^{(24,26)}$according to which the compound nucleus emits a second evaporation neutron whenever, after the emission of the first neutron, it has sufficient energy to do so. He obtained the following expression for the (n,2n) cross section:

$$\sigma(n,2n) = \sigma_{ne} \times \frac{\sigma_{n,M}}{\sigma_{ne}} \times \frac{\sigma(n,2n)}{\sigma_{n,M}}$$

where

$$\sigma_{ne} = \pi\left[0.12(N+Z)^{1/3} + 0.21\right]^2 \qquad \text{(reference 31)}$$

$$\frac{\sigma_{n,M}}{\sigma_{ne}} = 1 - 1.764\, e^{-18.14(N-Z)/A} \qquad \text{(reference 26)}$$

$$\frac{\sigma(n,2n)}{\sigma_{n,M}} = \frac{\int_0^{E_n - EB1} \varepsilon\, \sigma_c\, e^{4a(E_n-\varepsilon)^{1/2}}}{\int_0^{E_n} \varepsilon\, \sigma_c\, e^{4a(E_n-\varepsilon)^{1/2}}}$$

$$= 1 - \left\{ e^{p^{\frac{1}{2}}}\left[(1-q)p^{3/2} - (3-q)p + 6p^{1/2} - 6\right] + 6 - pq \right\} \times \left\{ e^{(pq)^{\frac{1}{2}}}\left[-2pq + 6(pq)^{1/2} - 6\right] + 6 - pq \right\}^{-1} \; ; \quad \sigma_{n,M} = \sigma_{n,n'} + \sigma_{n,2n} + \sigma_{n,3n}$$

$$p = 4aEB1 \quad ; \quad q = \frac{E_n}{EB1}$$

$$a = 0.154\,(\bar{J}_Z + \bar{J}_N + 1)\,A^{1/3} \ \text{Mev}^{-1}$$

ε = enrgy of the neutron emitted from the compound nucleus.

σ_{ne} = non-elastic cross-section

N = neutron number

Z = proton number

EB1 = separation energy of one neutron from the target nucleus

E_n = incident neutron energy in the center-of-mass system

σ_c = formation cross-section of the compound nucleus (assumed constant

A = atomic mass number

$\bar{j}_N, \bar{j}_Z$ = "effective" spin values

EB2 = separation energy of two neutrons from the compound nucleus. According to Pearlstein, the theoretical results based on the statistical model can not be considerably differentiated from the experimental data. Nevertheless, structure effects in the (n,2n) cross-sections against a statistical theory bachground have been observed for quite some time(27). Bormann(28) has discussed shell-model effects in (n,2n) cross-sections on even-neutron target nuclei. Since then, the subject has been open to controversy. For example, Rieder(29) has indicated lack of significant shell effects for target nuclei of neutron number close to 50. Similar results were shown by Hille(30). Even though he agrees that strond dependence of (n,2n) cross-section on the assymetry factor (N-Z)/A exists, he claims that shell effects can only represent a second order correction. While he does not completely exclude the possibility of shell effects, he states that no clear evidence in their support exists.

In conclusion, (n,2n) cross-section can be treated as statistical model cross-section with some superimposed structure of uncertain origin. Therefore, accurate experimentally measured cross-section data and (n,2n) neutron spectra are greatly in demand.

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LUNCHEON MEETING

Leasing — A Funding Approach to Accelerator Acquisition
Jack R. Templeman

LEASING - A FUNDING APPROACH TO ACCELERATOR ACQUISITION

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Technical Equipment Leasing Corporation
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Mount Vernon, New York   10552

In the last two years there has evolved a significant change in the funding market of available monies to purchase new equipment. There has been a dramatic cutback in the amount of government and state grants for capital equipment. Recent increase in the prime rate and taxation structure have also influenced industrial spending. The possible cancellation of the 7% Investment Tax Credit will further add to the industrial funding problem.

Many of these organizations have not suffered cutbacks with OPERATING FUNDS. Most types of operating funds can be used for leasing or rentals. Remember that it is not ownership of equipment that produces results, but rather USE of equipment. Leasing can provide this use of equipment while utilizing operating funds.

Many companies have used leasing as a very effective marketing tool to increase sales. Technicon Corporation with its combinations of autoanalyzers ranging in price from $5,000 to $65,000 has dominated that market. They have both a leasing plan and a 90 day cancellable rental plan. IBM and the other computer manufacturers have enjoyed the advantages of leasing and rentals programs with proven records of growth and the creation of secondary markets. Perkin and Elmer, Picker Corporation, Varian and many of the other companies serving the medical and scientific field have a large segment of their sales from leases. There hasn't been too much activity in the accelerator field with leasing. The volume of orders obtained by leasing for the different accelerator manufacturers range from 20% to none. The reasons for this can be categorized in two general areas: 1) previous availability of funds for outright purchase, and 2) lack of knowledge or understanding of leasing by the manufacturer, customer, and customer's purchasing procedures. In the past when more government grants were available for accelerator acquisition there was no need to lease equipment or to have knowledge of how it could be used. Manufacturers shied away from leasing since funding was not a problem and they didn't want to get involved in the customers financial problem. On the other hand most customers didn't know that operating funds could be used in many cases to lease equipment either as a short term approach to financing while additional funds become available or as a method of spreading out funding over a number of years. The same holds true for their purchasing procedures; either they had the money or they waited until the full funding was approved. Both manufacturers and customers are now finding that leasing may be the only way certain customers can acquire equipment until the money market changes.

Leasing compares very favorably in today's money market as a source of secondary funding. U.S. Steel can obtain money at the prime rate of 7 1/2%. However on any long term debt a borrower is required to keep $1.00 in the bank for every $5.00 borrowed. This means that if they borrow $100,000 they must maintain a compensating balance of $20,000 in the bank. In terms of effective interest rate this increases that initial loan by an additional 1 1/2%. So U.S. Steel is really paying an effective rate of 9%. Any organization with less than an AAA credit rating may be paying more for their money. The simple interest rate for leasing in today's money market is approximately 11 to 12%. A car loan may have an effective rate of 18%.

Indicated below is an example of cost comparison between a 4 year lease, a 4 year bank loan, and a cash purchase program assuming a $50,000 system with an 8 year depreciation life and a tax bracket of 48%. The depreciation is based on an 8 year life using an accelerated double declining balance method.

4 Year Lease - $50,000

	4 Yr. Cumulative Cost	
Rental	Tax Savings	Net Cash Cost
$1295/mo.	48%	
$62,160	$29,837	$32,323

4 Year Bank Loan - $50,000

7 1/2% Simple Interest

4 Year Cumulative Cost

Payments	Depreciation	Int.	Tax Savings	Net Cash Cost
$1208.75/mo.	(8 Year Life)		48%	
$58,020	$38,135	$8020	$22,154	$35,866

Cash Purchase - $50,000

4 Year Cumulative Cost

Cost	Depreciation (8 Year Life)	Tax Savings 48%	Net Cash Cost
$50,000	$38,135	$18,305	$31,695

The Cash Purchase Program does not reflect the benefits that a company can obtain by keeping the extra working capital for other uses that would yield a higher return than the cost of a lease or bank loan. The 7 1/2% bank loan would also require a compensating balance of 20% ($10,000) to be tied up with the bank. With the lease concept the equipment can be readily exchanged for more sophisticated equipment without the complication of trade-ins at the end of 4 years.

There are many reasons why leasing is becoming more popular.

1) Conservation of funds: The total cost of the equipment does not have to be paid out at one time but can be spread over a number of years. This conserves funds for other equipment or expenses where leasing may not be feasible.

2) Avoids red tape: The decision to lease and use operating funds can normally be made at a lower management level and does not require approval of a budget committee or top management. Speeds up delivery.

3) NIH, AEC, NSF: Allow OPERATING FUNDS to be used for

rentals or leases without special approval. However, any changes in the use of CAPITAL FUNDS over a certain value normally require special approval. The government does not have a policy for or against leasing.

4) Hedge against obsolescence: Shorter term leases allow trade-ups or replacements to be made more in tune with rapid scientific changes.

5) Depreciation: Leasing may allow an accelerated recovery of equipment funds as an operating expense instead of a normal depreciation schedule. This would be true where the term of the lease is shorter than the normal depreciation schedule; i.e., 4 year lease term vs a 8 year normal depreciation schedule.

6) Hedge against inflation: Equipment can be leased with the value of today's money but paid with money in future years that may have less purchasing value.

7) More equipment now: Leasing will allow more accessories and other items to be obtained now with a smaller yearly financial expenditure.

8) Reimbursements: Since most leases can be treated as operating expenses there may be a rapid recovery through taxes, Blue Cross, Medicare, or other types of equipment reimbursement accounting.

9) Pay as you go: If the equipment is income producing

the cash flow for monthly rentals may be completely offset by the income from the services rendered. Most profit and non-profit organizations can turn over their own funds with a 15% yield or greater. As long as the cost for leasing is less than that yield, the cash flow will be to their advantage.

10) Future decision making: At the end of the lease term the lessee can decide to renew the lease for a nominal amount, take title to it by exercising a purchase option, trade up to new equipment, or return it with no future obligation. The important point is a decision must be made at the end of the lease term. Too often equipment that is purchased and depreciated ends up being junked way past its useful life. Considerable maintenance, storage, and other cost factors may be involved that would have been resolved in a more economical manner if the equipment was not owned by the user. Leasing allows newer equipment to be obtained before obsolescence and excess costs occur.

Leasing does have its limitations in that the lessee surrenders title to the equipment and has to pay an additional amount to take title to the equipment. However, obsolescence may negate this disadvantage. If the term of the lease and the life of the equipment approach each other, the accelerated operating expense advantage vs depreciation will be overshadowed.

Both manufacturers and customers are looking more favorably on leasing today as a way to fund equipment acquisition. A larger part of the equipment funds available will be used for leasing since both manufacturers and customers are becoming lease orientated. This belief is shared by manufacturers already using leasing, customers with leased equipment, and the leasing companies.

SESSION II: APPLICATIONS IN MEDICINE

Chairman: John S. Laughlin

*Trends in Medical Application of Small Accelerators
John S. Laughlin

Machine Problems in Generating Neutrons for Tumor Therapy
Marshall R. Cleland

*Operation of a Medical Cyclotron for the Production of Radioactive Isotopes
James P. Mamacos

The LINAC in Radiology
Robert J. Schulz

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*Manuscript not available for publication.

MACHINE PROBLEMS IN GENERATING NEUTRONS FOR TUMOR THERAPY

by

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Radiation Dynamics, Inc.

Westbury, New York

INTRODUCTION

Neutron Therapy

The effects of fast neutron radiation on cancer cells have been under intensive investigation in a number of medical centers for more than ten years (1,2,3,4). The accumulating evidence now indicates that neutrons offer certain advantages over X-rays and gamma rays in the radiation treatment of tumors (5,6). The primary advantage is the suppression of the oxygen effect which complicates the response of large, solid tumors to X-rays. Other differences are the reduced probability of cell recovery from partial radiation damage and the reduced radiation absorption in bone as compared to soft tissue. These effects may prove to be advantageous in certain cases. The clinical aspects of neutron therapy as applied to human patients are now being studied at the Hammersmith Hospital in London with favorable results (7). A good review of the present state of knowledge in this field, including a discussion of various neutron sources and their characteristics is given in reference (6).

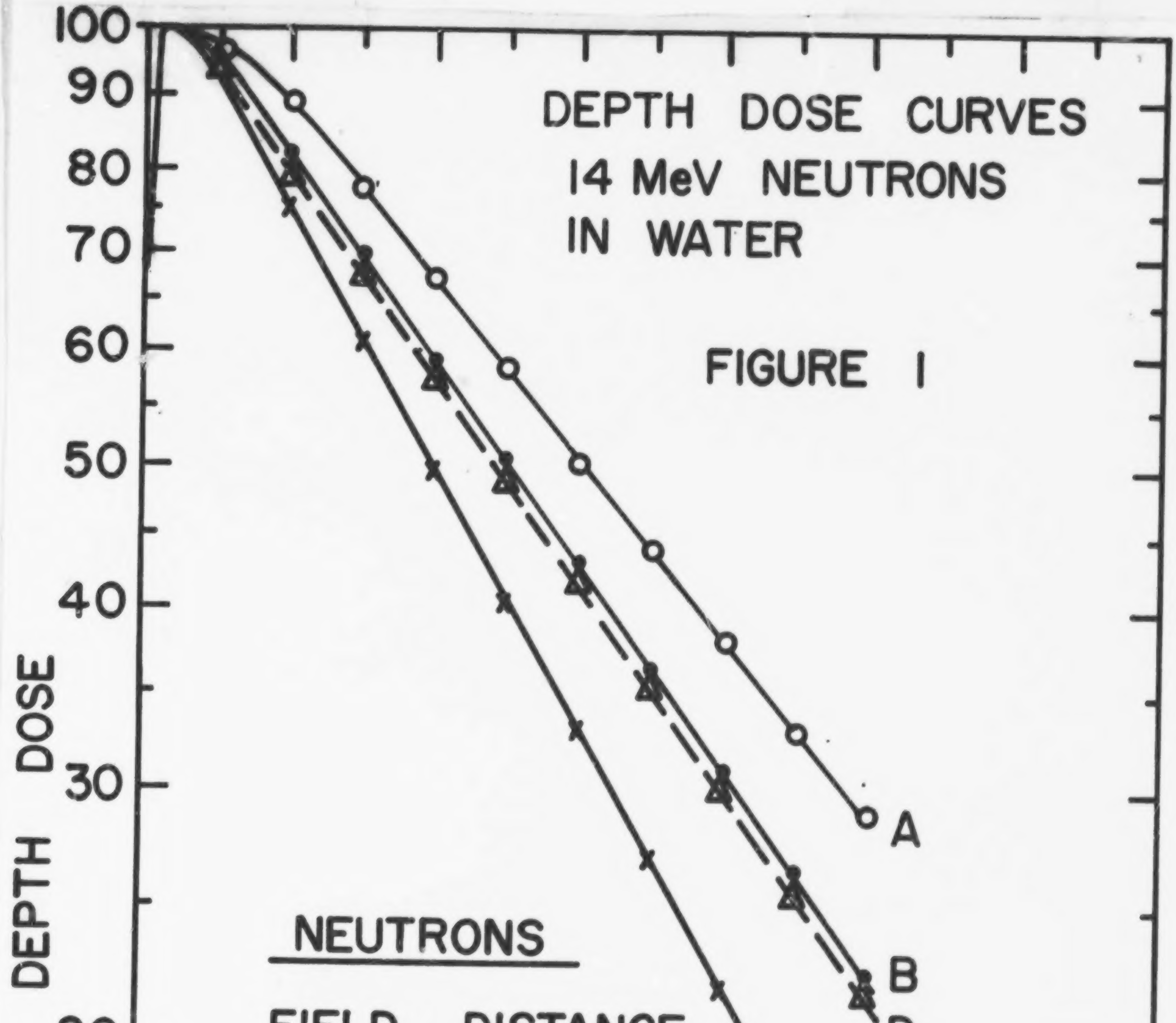
Neutron Sources

Neutrons exist in the nuclei of all atoms except ordinary hydrogen, but they can only be released during nuclear transformations caused by energetic nuclear collisions. Intense beams of free neutrons are obtained from nuclear reactors but the average neutron energy (only a few MeV) is too low for deep therapy applications. Small cyclotrons have been used to produce neutrons of a broad range of energies using the $Be^9(d,n)B^{10}$ reaction (8,9). The average neutron energy from a 7.4 MeV deuteron machine is about 4 MeV and the 50% depth dose occurs at about 5 centimeters in soft tissue. The average neutron energy from a 16 MeV deuteron beam is higher, about 6 MeV, and the 50% depth dose occurs at about 8 centimeters (6). This quality is comparable to 230 kV X-rays (9).

The best neutron energy spectrum for deep therapy is obtained using the $H^3(d,n)He^4$ reaction. This yields neutrons of a single energy, about 15 MeV, which produce a depth-dose distribution better than 250 kV X-rays but not as good as Cobalt-60 gamma rays (10,11). (See Fig. 1). The 50% point occurs at a depth of 10 cm with an SSD of 125 cm and a field size of 5 x 5 cm (6). This "D-T" reaction has the additional important advantage that the energy of the bombarding particle need be only a few hundred kilovolts. This means that the neutron generator can be relatively small, mobile and inexpensive.

Neutron Intensity

General clinical experience with X-ray and gamma-ray therapy has shown the need for a radiation intensity high enough to deliver a dose of about 300 rads in 10 minutes.



DEPTH DOSE CURVES
14 MeV NEUTRONS
IN WATER

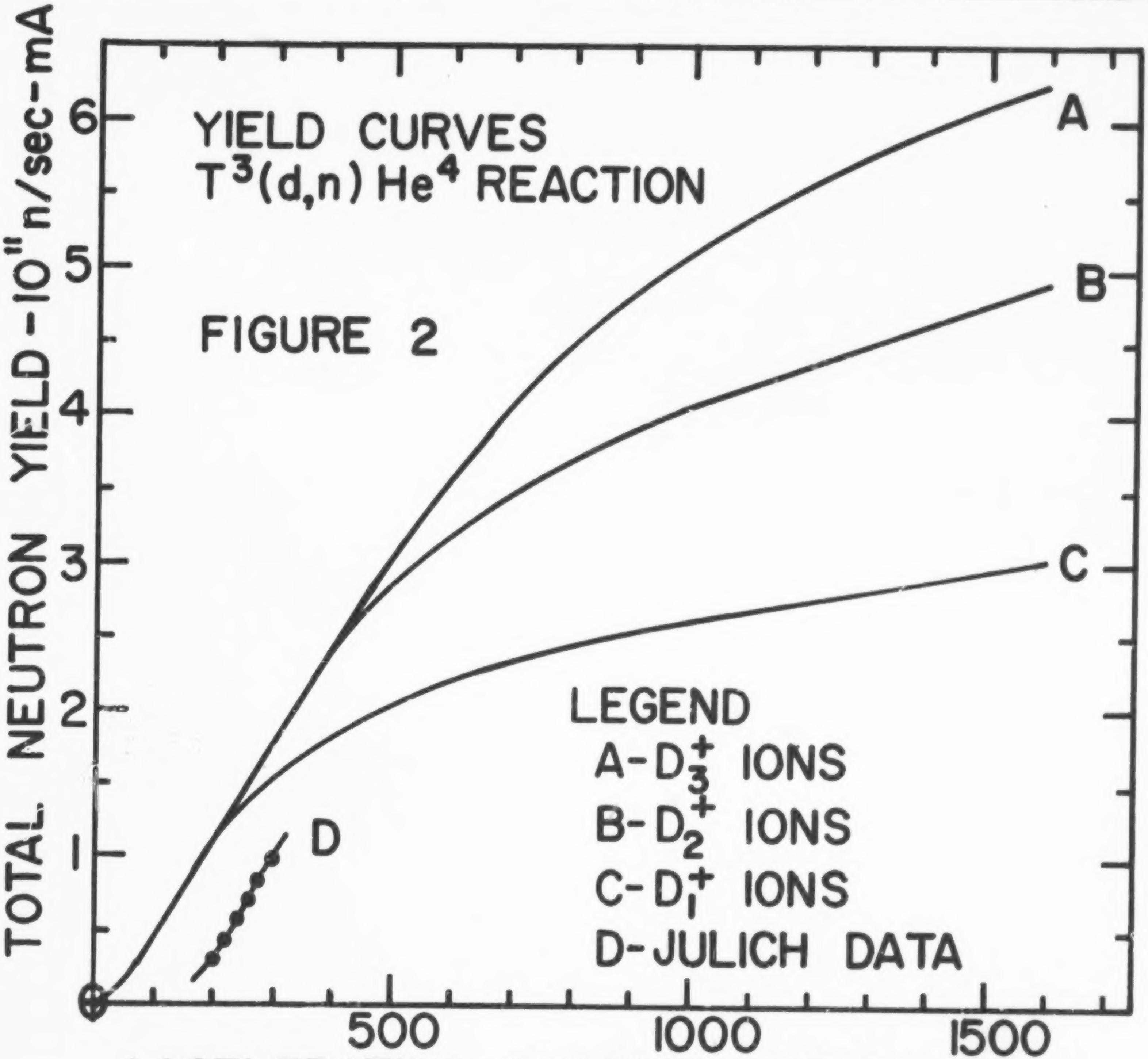
FIGURE I

With fast neutrons a dose of 100 rads in the same time would be sufficient because of their higher relative biological effectiveness. This requires a 15 MeV neutron flux at the skin of about 2.7 x 10^7 neutrons per square centimeter per second (12). The total neutron yield (isotropic) at the accelerator target must be nearly 1 x 10^{12} neutrons per second in order to produce this flux at a treatment distance of 50 cm. In order to meet the preferred requirement of a 50% depth dose at a tumor depth of 10 cm with small field sizes, it will be necessary to use a treatment distance of 125 cm so as to reduce the attenuation due to the inverse square law (6). In order to maintain the dose rate at this distance, it will be necessary to have a neutron yield of about 5 x 10^{12} n/sec.

Neutron Yield

The theoretical D-T neutron yield from a thick tritium-titanium target increases with the beam energy as shown in Fig. 2 for the three ionic species of deuterium (13,14). The T:Ti atomic ratio is assumed to be 1:1. The typical beam from a duoplasmatron-type high-current ion source contains nearly equal amounts of these deuterium ions and the average neutron yield should follow the D_2^+ curve approximately. The yield rises rapidly up to about 500 keV bombarding energy and continues to rise at a reduced slope up to 1500 keV and beyond.

Practical yields obtained with commercial targets are limited to about 2/3 of these theoretical values in the 300


YIELD CURVES
T3(d,n) He4 REACTION
FIGURE 2
LEGEND
A-D3+ IONS
B-D2+ IONS
C-D1+ IONS
D-JULICH DATA
A
B
C
D
TOTAL NEUTRON YIELD-10¹¹ n/sec-mA
1
2
3
4
5
6
500
1000
1500
ACCELERATING VOLTAGE - KILOVOLTS

to 400 keV range (15,16,17,18). The reason for this discrepancy is not well understood at this time, but may be due to the presence of inert material at the surface of the target. This might be organic contaminants from pumps and gaskets or it might be titanium which does not contain the normal amount of tritium (19). This explanation is strongly suggested by the experimental data points shown in Fig. 2. These were obtained with the 300 keV, 8 mA machine built by RDI for the Nuclear Research Establishment at Julich, West Germany. The data would fit the theoretical curve B, if one assumed a mechanism for the loss of about 125 keV of beam energy before reaching the active part of the target.

If, for the moment, one accepts this idea, then the neutron yield from a 500 keV machine with a mixed deuteron ion beam should be about 2.3×10^{11} n/sec-mA and a beam current of 22 mA should be sufficient to generate a source strength of 5×10^{12} neutrons/second.

SURVEY OF D-T GENERATORS

Sealed Tube Sources

In this type of neutron generator the target, which may be a block of titanium or erbium, is loaded with both deuterium and tritium atoms by beam bombardment. The tube contains a mixture of deuterium and tritium gases at a low enough pressure to insulate about 150 kV. An RF or PIG type ion source at one end makes use of this gas to form a mixed beam of deuterons and tritons which are then accelerated to the target by the applied high voltage.

There are three suppliers of such tubes at this time. They are; Kaman Nuclear in Colorado Springs, Colo., USA (20), The Services Electronics Research Laboratory, Baldock, Herts, U.K. (21), and the Philips Research Laboratories, N.V. Philips Gloeilampenfabrieken Eindhoven, Netherlands (22). The Philips' tubes are sold in the USA by Amperex Electronics, New York.

These sealed tube generators are attractive from the standpoint of tritium safety and very long operating lifetimes. The Philips' unit in particular has demonstrated a useful life of several thousand hours. The neutron output, however, is too low at this time to be considered for therapy applications, the maximum yield being about 1 or 2 x 10^{11} neutrons/second. One reason for the low yield is the low operating voltage of these gas-filled tubes. Another is the fact that with both deuterons and tritons in the beam and in the target, there are four different combinations for collisions in the target. Only two of these, D-T and T-D are useful in producing high energy neutrons. The D-D and T-T collisions are wasted. Also, the accelerated tritons are not as effective as the deuterons in the beam due to the kinematics of the reaction.

The net result is that the neutron yield per milliampere of beam current is about three times lower than for a pure deuteron beam bombarding a tritium target. Nevertheless, the SERL group is actively working on a large, sealed-tube device which is intended for neutron therapy applications with an output of at least 1 x 10^{12} n/sec (23).

Low Power Deuteron Accelerators

These machines utilize the conventional technique of accelerating a pure deuteron beam onto a tritium-titanium target. The accelerating voltage is usually in the 100 to 400 kilovolt range. The beam current may be from 1.0 to 4.0 mA and is usually obtained from an RF or PIG ion source. Several commercial suppliers make machines of this type including Texas Nuclear of Austin, Texas, Accelerators, Inc., also of Austin, SAMES of Grenoble, France, 20th Century Electronics, Ltd., of New Addington, Croydon, Surrey, U.K., and Kaman Nuclear of Colorado Springs, Colorado. The neutron yields from these machines are also limited to about 2 to 4 x 10^{11} n/sec. They are widely used for neutron activation analysis and for research in neutron physics, but are not interesting for therapy.

High Power Deuteron Accelerators

Several machines have been built for special applications which have very high neutron outputs suitable for cancer treatment. None of these are being used for this purpose now, but their existence indicates the practicality of this kind of neutron source.

The RDI machine at Julich, West Germany operates at 300 kV with a mixed deuteron ion beam of 8 mA maximum, yielding a neutron output of about 8 x 10^{11} n/sec (24,25). The machine is air-insulated and is continuously pumped with a large oil diffusion pump and rotary forepump. This unit was built in 1968.

The HVE machine at Aldermaston, England is rated for 15 mA at 300 kV. This is a large, air-insulated unit which is capable of a neutron yield as high as 1.5 x 10^{12} n/sec (15). It was built in 1963.

Another large HVE machine is at the Lawrence Radiation Laboratory in Berkeley, California, USA. This is rated at 10 mA and 500 kV and can achieve a maximum output of about 2 x 10^{12} n/sec (26). It was built in 1965.

Texas Nuclear has recently built three high current, 300 kV machines for Texas A & M, College, Texas, The Goddard Space Flight Center, Greenbelt, Maryland and the Radiobiological Institute TNO, Rijswijk, The Netherlands. These can run at about 5 mA with a yield of about 5 x 10^{11} n/sec. The Dutch unit was built in 1968.

ORTEC of Oak Ridge, Tennessee has built a 25 mA, 300 kV, deuteron accelerator for NASA, Lewis Research Center, Cleveland, Ohio. This machine was built in 1967 and was not equipped with a tritium target. NASA is now developing a rotating drum type of target which will be tested before the end of 1969 (27).

Both SAMES of Grenoble, and Braun Boveri (BBC) of West Germany have recently announced their intentions to develop 300 kV, 10 mA machines with outputs of 1 x 10^{12} n/sec for therapy purposes.

Very High Power Deuteron Accelerators

In 1967 the USAEC built a 300 mA, 150 kV machine for Project Henre (28). This is equipped with a large target about one square foot in area containing about 2000 Curies of tritium. The neutron yield is about 1 x 10^{13} n/sec.

This machine has been placed on a high tower in order to measure the absorption and scattering effects of neutrons in the atmosphere, as part of a study of the effects of atomic weapons. The large size of the target would not be practical for a ciinical machine requiring a collimated neutron beam as the penumbra would be too large. However, it would be possible to reduce the beam diameter by utilizing an external magnetic lens.

Another USAEC project, the DCX hydrogen fusion experiment at Oak Ridge, Tennessee provided the stimulus for the development of the most powerful deuteron accelerator in existence (29). This machine is a very large, air-insulated device built about 1960. It can provide a deuteron current of 300 mA at 600 kV. Acceleration takes place in four gaps of 150 kV each. The beam can be focused down to a few centimeters diameter by means of an external solenoidal lens. Strange beam optical effects have been observed at the focal spot due to the very large space charge forces produced by the beam itself. This machine has never been used as a neutron generator, but it shows the state of the art for deuteron beam production. If a suitable tritium target could be made for it, the neutron yield might go as high as

8×10^{13} n/sec.

TRITIUM TARGET LIMITATIONS

Cooling

The typical tritium-titanium target coating must be well cooled to prevent evaporation of the tritium into the vacuum chamber of the accelerator. The surface temperature must be held below about 250°C (30). This is not a difficult problem, and can be solved by means of a high pressure, high velocity water cooling system. A beam power density of about 750 watts per square centimeter can be handled in this way on a stationary target (31). A one inch diameter target can be expected to work with a total beam power of up to 4 kV.

Deuterium-Tritium Displacement

Even when the target is properly cooled, there is a steady loss of tritium from the target and a consequent reduction in the neutron output. This is believed to be caused by the displacement of tritium from the titanium layer by deuterons which come to rest in the target. This explanation is supported by the data given in Fig. 3, which shows the decay of D-T neutrons and the build-up of D-D neutrons from the RDI Julich machine. The half period is about the same, 30 minutes, for both of these processes. The similarity of these times has also been reported by others (15).

Because of this displacement mechanism, an increase in beam current to achieve a higher neutron yield will propor-

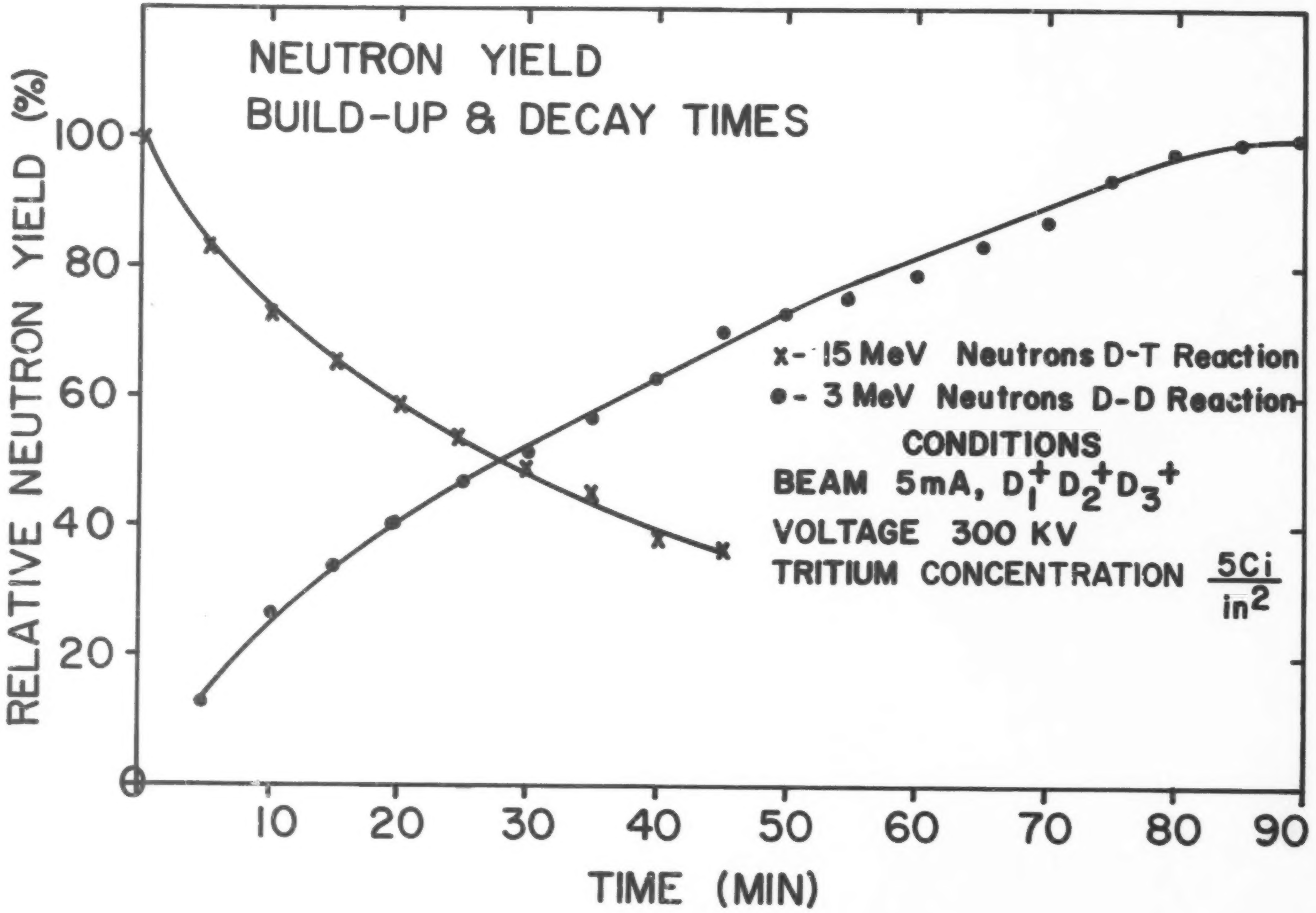

NEUTRON YIELD
BUILD-UP & DECAY TIMES
RELATIVE NEUTRON YIELD (%)
100
80
60
40
20
TIME (MIN)
10
20
30
40
50
60
70
80
90
x - 15 MeV Neutrons D-T Reaction
● - 3 MeV Neutrons D-D Reaction
CONDITIONS
BEAM 5mA, $D_1^+ D_2^+ D_3^+$
VOLTAGE 300 KV
TRITIUM CONCENTRATION $\frac{5Ci}{in^2}$

FIGURE 3

tionately reduce the target lifetime. The total number of neutrons obtainable from a given target is a fixed quantity which, of course, depends on the tritium concentration and the range of the deuterons in the target material.

Rotating Targets

A practical solution to the problem of increasing the yield without reducing the lifetime is a high-speed rotating target. This increases the useful area of the target and, therefore, the available tritium without requiring an increase in beam diameter.

The LRL target (26) operates routinely with 8 mA of deuteron beam at about 400 kV energy with a beam diameter of less than 2 cm. The average beam power is 3.2 kW and the power density about 1000 wats/sq. cm. The target half-life is as high as 40 hours under these conditions. Other rotating target systems are offered commercially by Multivolt Ltd., Crawley, Sussex, England, and Nukem, Wolfgang bei Hanau, West Germany. The rotating drum target under development by NASA (27) will be interesting because of its very large surface area.

DYNAGEN IV DESCRIPTION

General

The Dynagen IV system is a high intensity neutron generator designed especially for tumor therapy. It is being built by RDI for the Cleveland Clinic. It is essentially a high current deuteron beam accelerator with a high-power rotating tritium target and a large neutron collimator.

Power is supplied by cable from a separate high voltage generator and operation is controlled from a remote console. The collimator port is oriented at 90° to the accelerator axis so as to provide a vertical neutron beam from a horizontally mounted machine. This reduces the overhead space required in the treatment room. Treatment time is controlled by an integrating radiation monitor which shuts off the machine when the patient has received the prescribed dose.

Ion Source and Controls

The deuteron ion beam is produced by a Dynamag ion source developed by RDI and used on its large research aceelerators (32,33). It is basically a duoplasmatron-type source and produces copious quantities of both atomic and molecular ions of deuterium. The molecular ions are especially useful for the production of fast neutrons from the D-T reaction. The power supplies which control the operation of the source are located within the high voltage terminal of the accelerator. The power for these supplies is provided through the high voltage cable by an isolation transformer located in the high voltage generator. The source is cooled by a closed-loop liquid heat-exchanger system which enhances the lifetime and reliability of the source.

Acceleration Tube and High Voltage Structure

The ion beam is accelerated through a multi-stage tube consisting of large-apertured metallic electrodes separated by large-diameter glass rings. The assembly is cemented together using a special epoxy resin which provides vacuum tightness and great mechanical strength. The electrodes are shaped to intercept scattered particles travelling in either direction. This protects the insulators and seals from radiation damage. The design also stabilizes the position of the beam on target and is an essential feature of this high current ion accelerator.

The tube is enclosed by a set of circular corona rings which suppress corona discharges from the accelerating electrodes. The intermediate potentials are obtained from a high impedance resistor string mounted on the tube. The tube and corona ring assembly is clamped to the base of the housing by means of spring-loaded insulating rods. This technique guarantees sufficient mechanical strength for horizontal mounting of the machine without subjecting the epoxy seals to tensile stresses.

Target and Vacuum System

The target consists of a tritium-titanium coating deposited on a water-cooled copper plate which is rotated at high speed to prolong the life of the coating. The half life of the coating is sufficient for routine clinical use and the plate can be easily replaced at regular intervals. The vacuum pumping system is a combination of a large titanium sublimation pump and a small getter-ion pump. This technique has been shown to be reliable for long periods of time on the ORTEC-NASA machine (34). The sublimation pump traps the tritium gas evolved from the target and reduces the tritium hazard during machine servicing. The small getter-ion pump is required to clean up residual argon gas and traces of organic contaminants which are not trapped by the sublimation pump. The neutron yield and target lifetime are enhanced by the cleanliness of this kind of pumping system.

Collimator and Neutron Dosimetry System

Since the neutron radiation is nearly isotropic, it is necessary to surround the target with a large collimating shield in order to protect the patient from whole body irradiation (9,35,36). The shield is a composite, including materials of high atomic number to stop primary neutrons. The leakage radiation through the shield is less than 1.0% of the useful beam intensity in the treatment port. It is sufficiently compact to permit a treatment distance as short as 75 cm. The field sizes can be varied from 20 x 20 cm to 5 x 5 cm by changing the collimating insert in the beam port. Aiming of the beam is facilitated by an internal light source which casts an image on the skin of the patient corresponding to the neutron field size.

The radiation exposure is measured by a pair of transmission-type ionization chambers. These are located inside the neutron shield in line with the treatment port. The total dose delivered to the patient is determined by integrating circuits connected to the ionization chambers. The treatment is terminated automatically when the preset dose has been delivered. Two identical measurement systems are employed for the safety of the patient providing fail safe and redundant operation. These are backed up by a timer for additional safety (37).

High Voltage Generator, Cable and Housing

The high voltage potential required for beam acceleration is supplied by a separate generator which need not be located in the treatment room. A low frequency, single phase doubler circuit of conventional design has been chosen for maximum reliability. The output voltage, although continuously variable from zero to maximum is set at maximum voltage for routine operation and is regulated against changes in line voltage or load current.

The high voltage power is connected to the accelerator through a large coaxial cable provided with a grounded outer sheath. Low voltage ac power for the ion source controls is brought in on the coaxial high voltage conductor. The cable bushings are located inside the generator and accelerator housings which are both grounded so that no high voltage terminals are exposed. The accelerator employs gaseous SF-6 insulation which reduces its size and weight and simplifies maintenance procedures.

Remote Control Console

All operational controls are in the remote console which must be located outside the treatment room. Routine procedures are set up on a simplified control panel by selecting the voltage, current and total dose to be delivered. Numerous auxiliary functions are included for the convenience of technical personnel during adjustment procedures. Failure of critical components or sub-systems will shut off the machine and the fault will be indicated by a light on the console. The integrating dosimeter displays the instantaneous dose rate as well as the accumulation of total dose to the patient.

Performance specifications and physical data are listed in Tables I and II.

TABLE I

PERFORMANCE SPECIFICATIONS

Voltage

Nominal	400 kV
Maximum	500 kV

Voltage Regulation

Nominal	± 5%
Maximum	± 2%

Voltage Ripple

Nominal	3% rms
Maximum	1% rms

Beam Current

Nominal	10 mA
Maximum	15 mA
Beam Composition	D_1^+, D_2^+, D_3^+
Beam Diameter	1.0 inch

Neutron Yield (initial)

Nominal	1×10^{12} n/sec
Maximum	3×10^{12} n/sec

Target Half-Life

Nominal	In excess of 10 hrs.
Maximum	In excess of 40 hrs.

TABLE II

PHYSICAL DATA

System	Length	Width	Height	Weight
Accelerator	60"	48"	72"	5,000 lbs
Collimator	60"	60"	60"	35,000 lbs
High Voltage Generator	90"	60"	72"	5,000 lbs
Control Console	42"	24"	72"	500 lbs

CONCLUSION

The evidence in favor of using 15 MeV neutron beams to treat cancer in human patients is rapidly accumulating in the medical literature (6). The machine requirement of 5×10^{12} neutrons/second is beyond the capacity of any commercial machine at this time. However, the state of the accelerator art, as demonstrated by various special systems, is such that this requirement can be met using known techniques. We can expect to see the rapid development of high output D-T neutron generators in response to the inquiries now coming from the leading medical research institutions.

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THE LINAC IN RADIOLOGY

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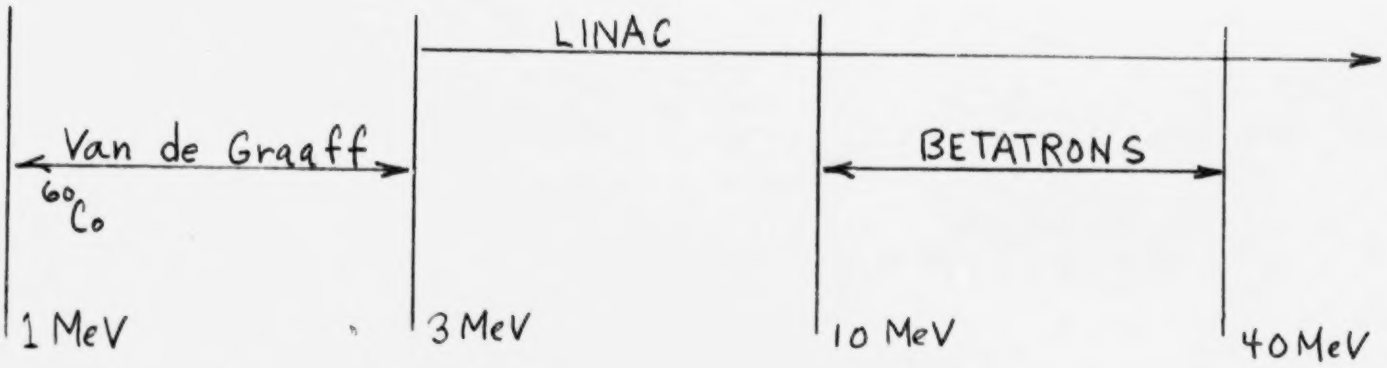
New York, N.Y. 10461

The LINAC in Radiology

I. Introduction. The place of the LINAC in radiation therapy:



In terms of beam energy, not beam power, there is no specific advantage of LINACs over betatrons for radiation therapy.

Both machines operate intermittently in that they produce pulses of radiation that last for 3-5 microseconds. The beam current during a betatron pulse is on the order of 0.5 milliamperes whereas medical linear accelerators usually have instantaneous currents greater than 100 Ma. The number of pulses per second produced by a betatron is fixed and the same as line frequency or in some machines 3 times line frequency. The pulse repetition rate of LINACs is variable from single pulsing to 300 pulses per second.

The x-ray or electron beam outputs from LINACs is considerably greater than those obtainable from betatrons and is probably the most important reason for the increased sales of LINACs for the past few years.

II. How LINACs work.

The major components of a LINAC are shown in figure 1.

1. A radio frequency (RF) power supply capable of producing instantaneous power levels on the order of megawatts at frequencies of, for example, 3000 megacycles (S-band).
2. A "modulator" that triggers the RF power supply and also the electron gun.
3. An accelerating waveguide into which the RF power and a pulse of electrons are simultaneously injected.
4. An "x-ray head" consisting of a bending magnet, x-ray target, monitor ionization chamber, etc.

As a result of the series of annular discs that are precisely spaced within the waveguide, see figure 2, the RF power sets up a traveling wave that bunches and accelerates groups of electrons down the length of the waveguide. It should be kept in mind that each bunch of electrons is separated by only 1/3 of a nanosecond so that during a 3 microsecond pulse the LINAC accelerates 9000 bunches.

The electron gun, see figure 3, is worthy of some individual discussion because it controls the number of electrons introduced into the accelerator and indirectly controls beam energy. The number of electrons injected is controlled by the bias applied to the anode disc. Since the level of RF power is held relatively

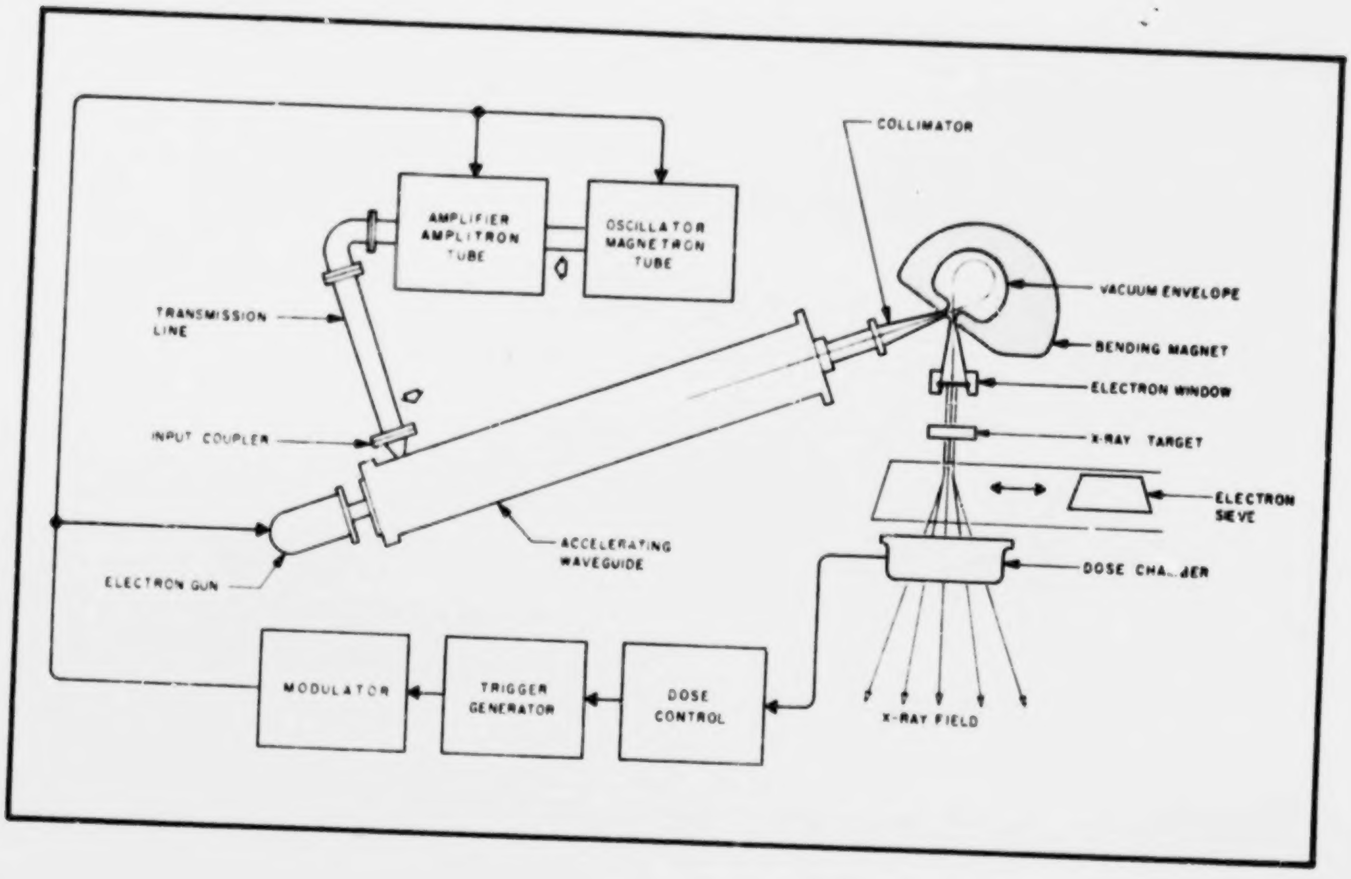

COLLIMATOR
AMPLIFIER AMPLITRON TUBE
OSCILLATOR MAGNETRON TUBE
VACUUM ENVELOPE
TRANSMISSION LINE
BENDING MAGNET
ELECTRON WINDOW
INPUT COUPLER
X-RAY TARGET
ELECTRON SIEVE
ACCELERATING WAVEGUIDE
ELECTRON GUN
DOSE CHAMBER
MODULATOR
TRIGGER GENERATOR
DOSE CONTROL
X-RAY FIELD

Figure 1.

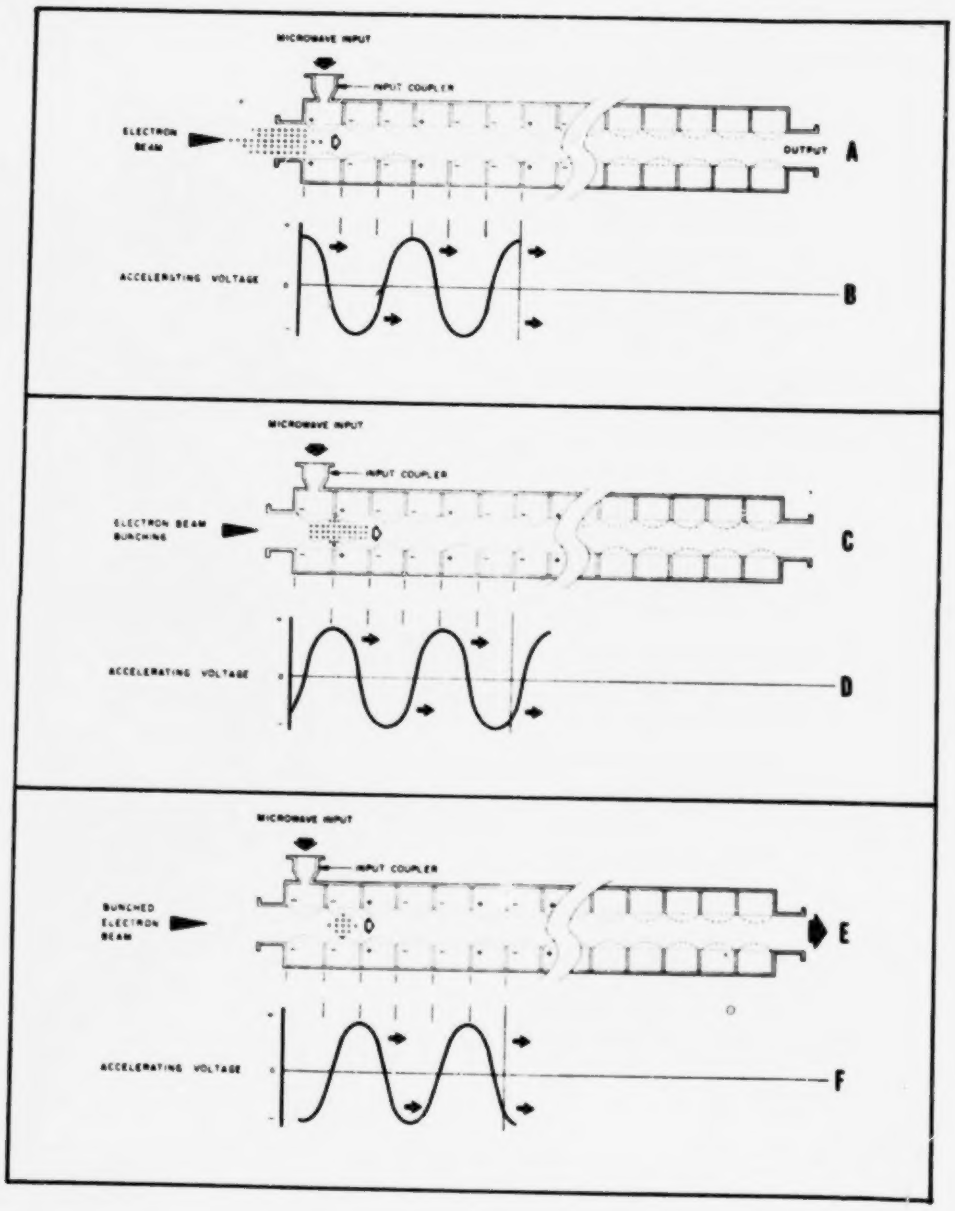

MICROWAVE INPUT
INPUT COUPLER
ELECTRON BEAM
OUTPUT
A
ACCELERATING VOLTAGE
+
0
-
B
MICROWAVE INPUT
INPUT COUPLER
ELECTRON BEAM BUNCHING
C
ACCELERATING VOLTAGE
+
0
-
D
MICROWAVE INPUT
INPUT COUPLER
BUNCHED ELECTRON BEAM
E
ACCELERATING VOLTAGE
+
0
-
F

Figure 2.

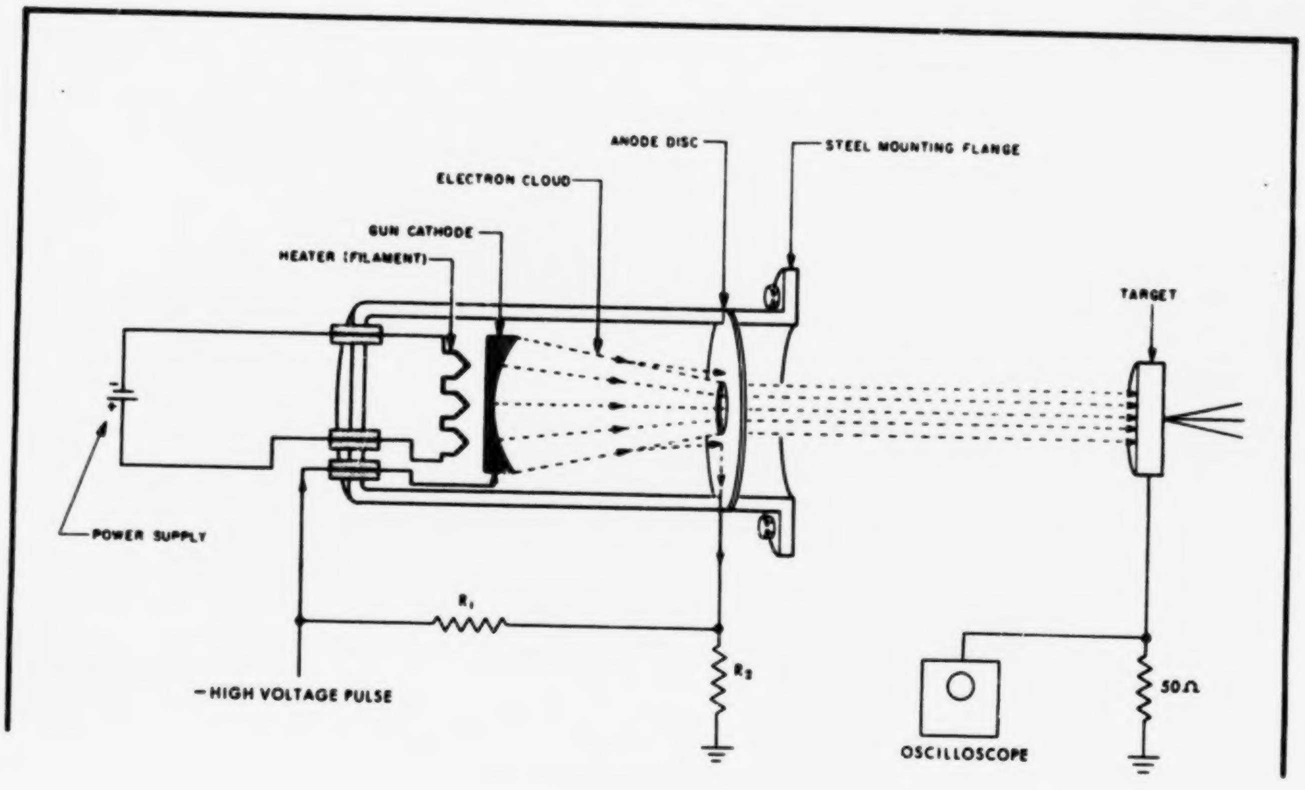

ANODE DISC
STEEL MOUNTING FLANGE
ELECTRON CLOUD
GUN CATHODE
HEATER (FILAMENT)
TARGET
POWER SUPPLY
R_1
R_2
– HIGH VOLTAGE PULSE
50Ω
OSCILLOSCOPE

Figure 3.

constant, a decrease in beam current results in an increase in beam energy.

On our 8 MeV accelerator,* we routinely monitor the amount of beam current collected in the x-ray target. This has turned out to be one of the most valuable parameters for checking the overall operation of the accelerator. Variations in any important operating parameter of the machine are immediately apparent as a change in the shape of the target pulse. In order to measure the target pulse it is of course necessary that the target be insulated from ground. A typical "target pulse" is shown in figure 4.

III. Clinical Applications.

Most medical LINAC's produce x-rays in the 3 to 8 MeV peak energy range. Although higher energy medical LINACs are becoming available, these are relatively expensive (0.6 megabucks) and complicated. The 6-8 MeV units used at the present time represent a compromise between the big machines and ^{60}Co teletherapy units.

Depth dose data for ^{60}Co, 8 MeV and 22 MeV x-rays are shown in figure 5. Although 22 MeV x-rays give the highest depth dose compared with surface dose, the high exit dose for most patients tends to negate this advantage.

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*Applied Radiation Corp. Mevatron 8.

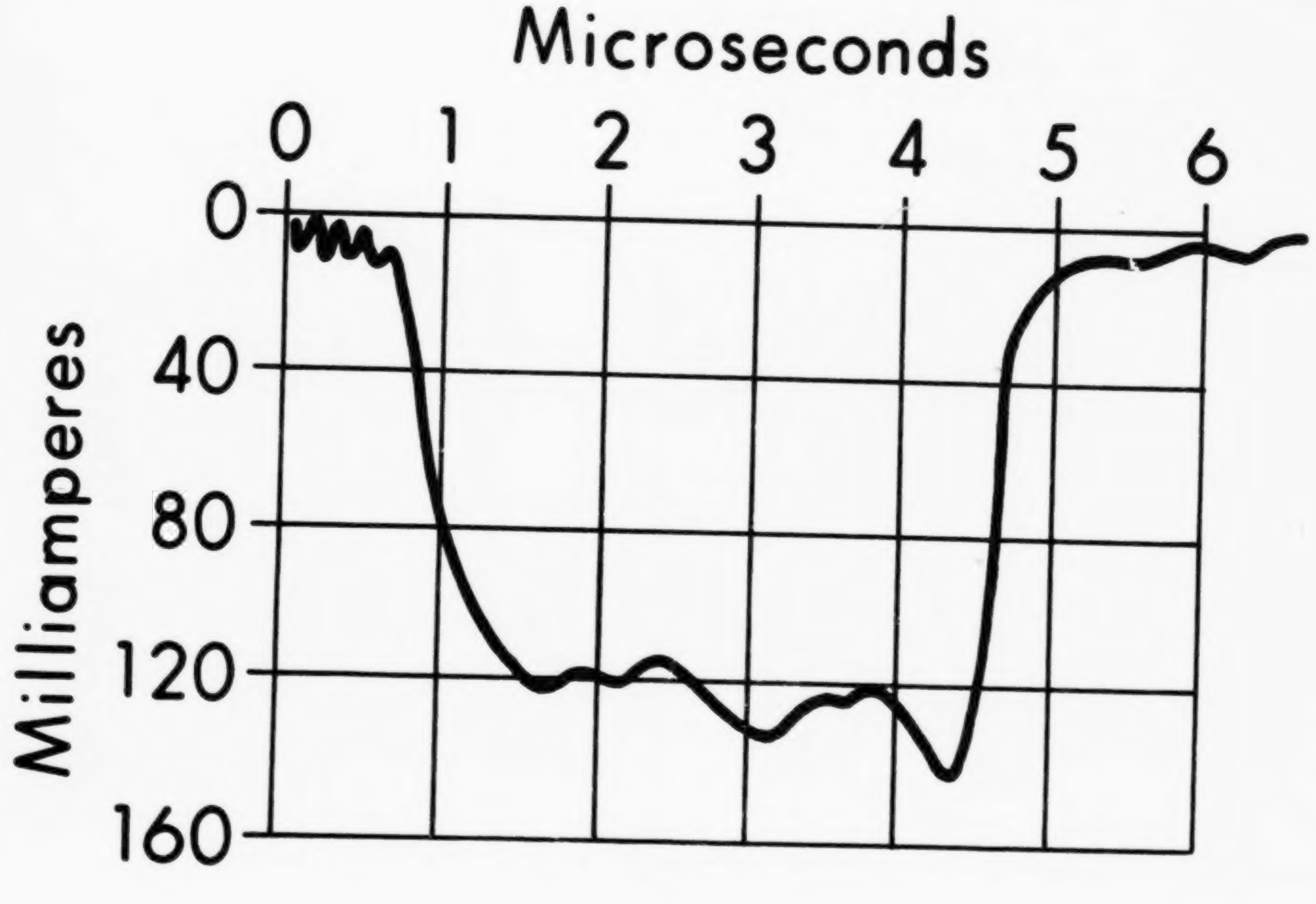


Figure 4.

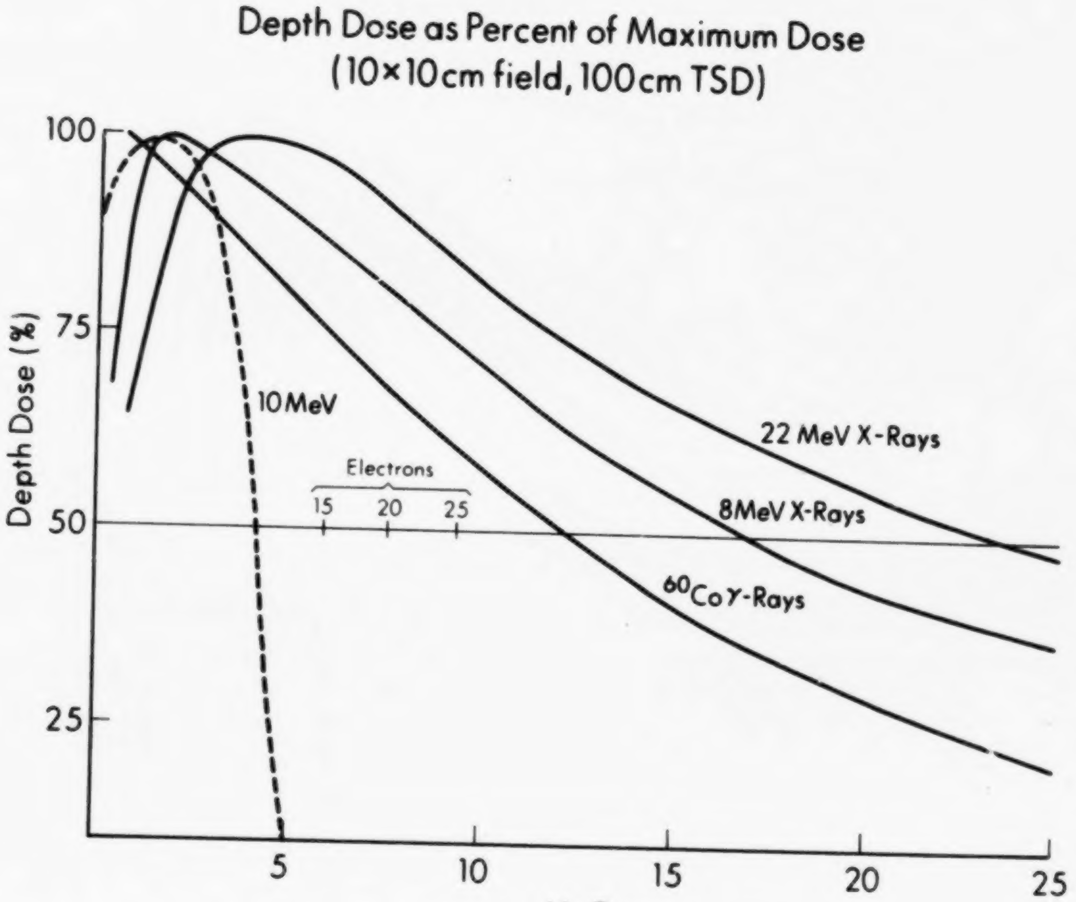

Depth Dose as Percent of Maximum Dose
(10×10cm field, 100cm TSD)
100
75
50
25
Depth Dose (%)
10MeV
Electrons
15
20
25
22 MeV X-Rays
8MeV X-Rays
60Coγ-Rays
5
10
15
20
25
H2O-cm

Figure 5.

Electron beam therapy with small LINACs has very limited applications and the main advantage of, for example, a 30 MeV LINAC is for electron beam treatment of deep-seated lesions.

Although their energy is low, 10 MeV, the power contained in the electron beam from a small accelerator can be high and may produce dose rates on the order of megarads per second. These beams presently have no clinical applications but they are very useful for sterilization, where megarad doses are required, and also for research in radiobiology.

As for high dose rate radiobiology, it has been shown by Hornsey and Alper, see figures 6 and 7, that the $LD_4 50$ is very dose rate dependent whereas the $LD_{30} 50$ is much less so. This dependency shows a marked change in direction at an average dose rate of 10,000 rads per minute. These rates are much higher than any used in clinical radiation therapy and are only available from LINACs.

We are presently repeating the work of Hornsey and Alper with our 8 MeV LINAC. Because the clinical dosimetry supplied with the machine will not work at these high rates, we have devised a different scheme for dose control and this is shown in figure 8. Electron pulses collected in a lead absorber are

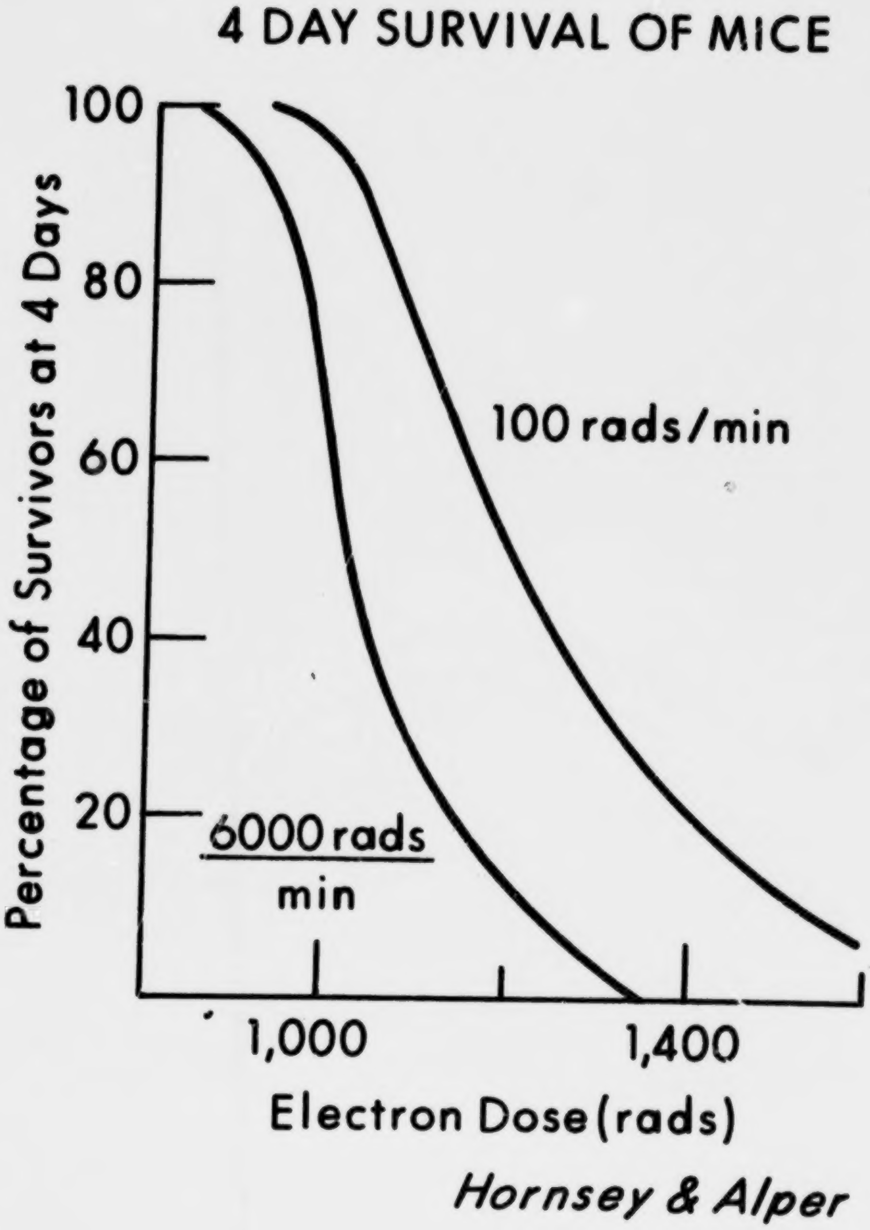

4 DAY SURVIVAL OF MICE
100
80
60
40
20
Percentage of Survivors at 4 Days
100 rads/min
6000 rads
min
1,000
1,400
Electron Dose (rads)
Hornsey & Alper

Figure 6.

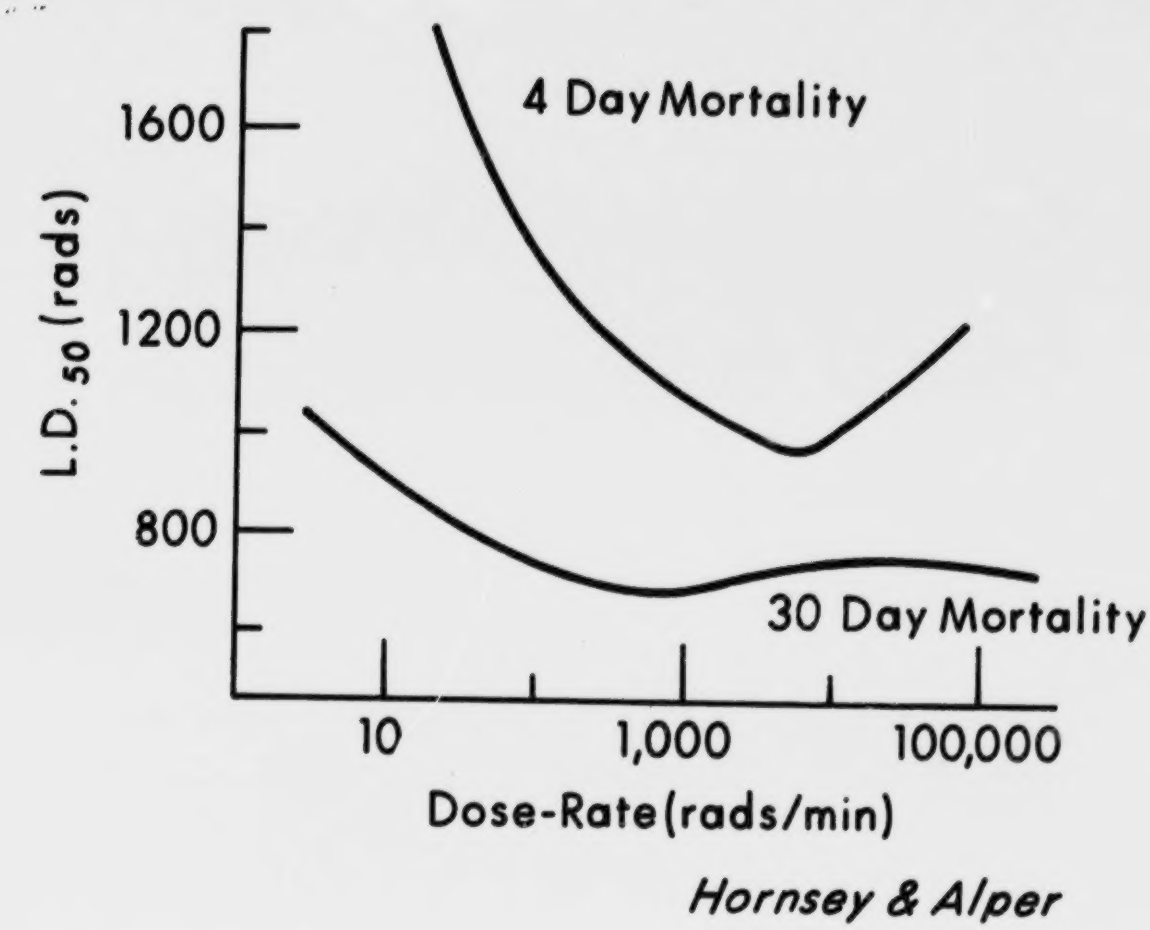
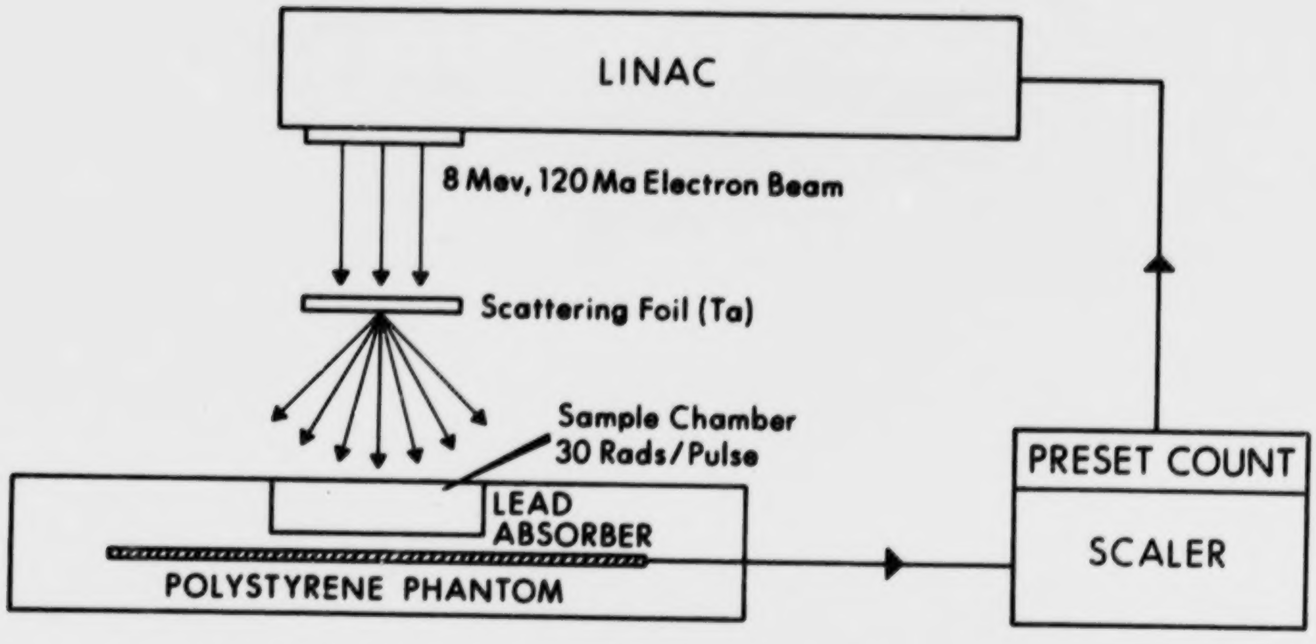

4 Day Mortality
30 Day Mortality
1600
1200
800
L.D.$_{50}$ (rads)
10
1,000
100,000
Dose-Rate (rads/min)
Hornsey & Alper

Figure 7.


LINAC
8 Mev, 120 Ma Electron Beam
Scattering Foil (Ta)
Sample Chamber
30 Rads/Pulse
LEAD
ABSORBER
POLYSTYRENE PHANTOM
PRESET COUNT
SCALER

30 Rads/Pulse = 2.6×10^7 Rads/min Peak Dose Rate
Average Dose Rates From 2000 to 26000 Rads/min

Figure 8.

counted by a standard laboratory scaler. The preset count circuit of the scaler is used to terminate electron exposure after a precalculated number of pulses have been delivered. The dose per pulse at a peak beam current of 120 Ma has been measured with ferrous sulfate at 34 rads.

SESSION III: APPLICATIONS IN INDUSTRY

Chairman: D. E. Wood

Industrial Application of 14 MeV Neutron Generators
J. E. Strain

*Activation Analysis in the Electronics Industry
James Cosgrove

*Ion Implantation with Accelerators
A. U. MacRae

*Electron Beam Processing
K. Morganstern

*Manuscript not available for publication.

INDUSTRIAL APPLICATION OF 14-MeV NEUTRON GENERATORS[1]

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ABSTRACT

The advent of a resonably low cost source of 14-MeV neutrons in 1956 stimulated a great amount of interest by research organizations in fast neutron reactions and their application to neutron activation analysis. There has been a much slower acceptance of the accelerator neutron source for use in industrial analysis. Fortunately since 1956 the cost of the neutron generator has decreased by a factor of two while the available neutron yield has increased by a factor of 10. As a result there is a renewed interest in their industrial application.

The results of an industrial survey are presented to show the present areas of application and examples of potentially useful reactions are discussed.

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[1] Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

INTRODUCTION

The development of small, low cost machine neutron sources has followed a rather interesting and torturous path. When the first low voltage accelerators for neutron production were built they were small sealed units that produced $\sim 10^6$ neutrons in short pulsed bursts with a pulse repetition rate of about 10 per second. Their major function was to replace isotopic neutron sources in educational and research applications.

As a result of the interest in these pulsed sources the development of the neutron generator diverged into two separate paths. The proponents of pure research and neutron activation analysis wanted progressively higher neutron fluxes while the application proponents in the petroleum industry needed even smaller generators with improved ruggedness and reliability.

The demands of the researchers for a generator with the maximum versatility resulted in the creation a small monster with accelerating voltage as high as 400,000 volts, an r.f. ion source for "pure" atomic ions, many stages of acceleration and a separable tritium target at the end of a very long drift tube. The performance of these machines are truly amazing. Neutron yields as high as 3×10^{11} neutrons per second are produced and electronic pulsing of the output is available with a full rise time of 0.25 micro seconds. Beam analyzing magnets are available so that only singly charged mono atomic ions strike the target thus restricting the energy spread of the produced neutrons. In addition to neutron production by the acceration of deuterium into a tritium target, almost any gaseous element can be ionized and accelerated when oil diffusion or turbo-molecular pumps are used to maintain the necessary operating vacuum. As you can well imagine the demand for extreme versatility caused the price of the accelerator to climb almost as fast as the number of possible applications. By 1963 the price had risen to the $20,000 to $30,000 range.

In about 1963 an effort was made to produce a true neutron generator whose sole purpose was to produce copious quantities of 14-MeV neutrons for neutron activation analysis. To increase neutron yield and improve the operating life of the unit, the acceleration system was simplified and the ion source was shifted to the more rugged penning ion source. The high voltage terminal was insulated by oil or pressurized gas. A neutron yield of 4×10^{11} n/s are produced continuously by this type unit using a beam current of 2.5 ma and an accelerating potential of 200 KV. Recently the development of the duo-plasmatron source that can operate at beam currents of 300 ma has been adapted to a neutron generator. This was an especially constructed neutron generator for neutron scattering and propagation experiments by the Health Physics Division at the Oak Ridge National Laboratory. The generator employed an Er-Tritide target with an area of 1,000 cm^2 and was intended to produce a neutron yield of greater than 10^{12} n/s for a minimum of 4 hours. The large target area was necessary to lower the beam density to the point that the neutron yield would have a reasonable life.

This mention of the target life brings us to the major limiting factor in attainment of high neutron fluxes. In our research at Oak Ridge we have found that maximum yield of a thick titanium tritide target is 7 x 10^7 n sec^{-1} per micro ampere of 150-keV duetrons and the time required for the neutron yield to decrease by a factor of two is 1,400μamp.hr. at a uniform beam current density of 300 μa cm^{-2}. To achieve the maximum neutron flux it is necessary to run at high current densities to concentrate the neutron producing surface as near the sample being irradiated as possible. Therefore if one uses a beam current of 2.5 ma on a 5-cm^2 target the beam density will be 500μamp cm^{-2} and the neutron yield will fall off to about one-half of the initial value in less than 30 minutes. This means only about 1.5 hours of irradiation time are available in a target before it must be charged at a cost of about 1 hour of down time and $50 in target costs. The issue is further complicated by the health physics requirements for handling and disposal of tritium contaminated waste. At an installation like the Oak Ridge National Laboratory the handling of radioactive waste is no problem, but at industrial locations the presence of a source of radioactive contamination can be a serious and costly problem.

To improve neutron generator life and eliminate the tritium problems neutron generators are again being developed as sealed tube units. The improvements in output and life are advancing rapidly and at the present time sealed tube neutron sources are commercially available with neutron yields of 10^{11} neutrons sec^{-1} and a life expectancy of greater than 100 hours. Unless there is a radical improvement in the target life of the drift tube generator model it would appear that the sealed tube neutron generator will be the model employed in the future by industrial concerns.

There are presently seven small neutron generators in the Oak Ridge Area. The Oak Ridge Associated University operate one as a full-time teaching device and the other six are employed in research and routine activation analysis. Two sealed tube units and one drift tube model are employed full time in the determination of oxygen in a variety of metals from beryllium to tungsten. The remaining three are employed in research in neutron physics, general activation analysis, and health physics research. To obtain a more complete picture of the application of neutron generators in the production programs of private industry a survey was conducted of those firms possessing neutron generators. The results were both disappointing and interesting. They were disappointing in that there are relatively few firms that routinely use neutron generators in production facilities and interesting in the wide range of applications of those firms that do employ nuclear techniques.

INDUSTRIAL SURVEY

In making the survey a list of industrial firms was taken from a compilation of names and addresses gathered by Dr. O. U. Anders of the Dow Chemical Company during the Activation Analysis Conference held at the National Bureau of Standards, Washington, D.C. in 1968. A deliberate effort was made to contact only those firms that employ neutron generators in a production capacity. While the survey is not complete it does to a large degree cover the range of industrial application.

Dr. O. U. Anders of the Dow Chemical Company reported that they have two neutron generators that are routinely used for the determinations of F, O, N, P, Si, Sn and Mg in a variety of organic compounds in the 1 percent to 10 percent range. Their sample load averages about 500 samples per month, and as an indication of Dow's interest in neutron activation they are now in the process of installing a Triga nuclear reactor for trace element determination as well as a broadly based research program.

Dr. Kenneth M. Fritz of National Lead of Ohio indicated they have been using a 150-KV neutron generator for the past 6 years. Their major application is in the determination of the purity of magnesium that is purchased as a feed material. This is done by determining the O/Mg ratio. Other applications include the determination of the isotopic ratio of uranium.

Dr. Ralph A. Johnson said that the Shell Development Corp. has been using neutron generators for about 10 years with a routine activation analysis program since 1964. Their 150-KV generator has been fully automated and is directly coupled to a computer data handling system. About 100 to 150 samples per month are analyzed for O, Si, P, and F. The type samples range from crude petroleum to the finished products. Since 1960 they have also used a 2-MeV Van de Graaff accelerator to produce (electrons to bremsstrahlung to photon neutrons) a thermal neutron flux for the nondestructive determination of V, Cu, Rh, Ir, Re, and other precious metals. Since 1967 they have made regular use reactor irradiations in trace element analysis.

Dr. John Orange reports that Gulf Research has been using neutron generator activation analysis since 1957 and now have two Cockcroft-Walton accelerators and one 3-MeV Van de Graaff for production of photoneutrons. Oxygen is routinely determined in crude to control the operation of their cracking plant. Their 14-MeV oxygen determination is automated and computer coupled to yield analytical results within 36 seconds after a sample is in the irradiation position. Their sample lead is increasing as fast as they are able to accept samples and presently runs at about 400 samples per month. Other analytical applications of their generators include the determination of Si in catalysts, P in carbohydrates, and V in crude oils.

Dr. Evert Wicker of U.S. Steel in Pittsburgh, Pa. has been using a drift tube neutron generator for the determination of O in about 500 samples per month of iron titanium steels as well as MnS and a variety of ore samples. Dr. Wicker indicated that all of their work was concerned with research steels and that there were no neutron generators used in commercial steel production.

Dr. Wendel Givens of the Mobile Research and Development Corp. is in the business of oil exploration using sealed tube neutron generators. These generators are truly remarkable devices. The neutron generator and either a neutron detector or a gamma ray detector are compressed into a 3-inch-diameter package to be lowered to depths of 5,000 feet into a bore hole. They produce up to 10^8 neutrons/seconds in short burst to enable logging the entire depth of a deep well by either a system of cyclic activation of neutron "die-away" measurements. These neutron generators are manufactured by several commercial firms and operate for hundreds of hours under extremes of pressure and temperatures up to 140° F. Other types of well logging include thermal capture cross section, capture gamma ray spectroscopy, and inelastic gamma ray scattering. The neutron generator well logging has been in use at Mobile for the past 9 years and its use has increased steadily. There are presently three commercial firms that do well logging with neutron generators as a service analysis.

There were several other companies whom I was unable to contact in the short time available for the survey although several applications should be reported because the techniques of the analysis have been thoroughly worked out and the application of a neutron generator offers a unique solution to a different analytical problem. The Purina Company is reportedly using 14-MeV neutron activation analysis to simultaneously determine O, N, and P in feed products. The U.S. Treasury is considering the use of neutron generators to determine with a high degree of accuracy (± 0.1 percent) the fluorine content of fluorspar. A Japanese firm as well as one American concern plan to use a neutron generator for the determination of ^{235}U in a nuclear reactor fuel recovery process.

SUMMARY

This survey clearly indicates that the oil and chemical oriented industries are in the vanguard of generator application to industrial problems. All of the persons contacted indicated the interest and application is slowly increasing in the wake of solid economical and technical achievement. The development of contamination free, rugged, and dependable neutron generators will greatly accelerate this trend.

ACKNOWLEDGEMENTS

The author wishes to express his thanks to those individuals and companies mentioned in this report who have volunteered the information on their neutron generator programs.

LUNCHEON MEETING

* The Radiation Control for Health and Safety Act of 1968 – How it may Affect Manufacturers and Users of Small Accelerators
John C. Villforth

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* Manuscript not available for publication - presentation not given.

SESSION IV: GENERAL AND SAFETY ASPECTS

Chairman: James McLaughlin

The Radiation Shielding Problem
E. Alfred Burrill

Practical Radiation Protection Measurements
Philip M. Lorio

A Solution to Tritium Pump Contamination for Small Accelerators
Robert Steinberg

*Neutron Radiography Utilizing A Small Accelerator
Norman Bostrum

The Use of Computers at Accelerators
James F. Mollenauer

*Manuscript not available for publication.

THE RADIATION SHIELDING PROBLEM WITH LOW-ENERGY ACCELERATORS

Presented by: E. Alfred Burrill
Consultant, Nuclear Marketing
and Technology
Portola Valley, California

at the ANS Symposium on Applications of
Small Accelerators
New York, New York
April 9, 1969.

1. INTRODUCTION

The solutions to the radiation-shielding problems of accelerators, large or small, are complicated mainly by a lack of quantitative information concerning the basic characteristics of radiations from accelerators, as well as their scattering within the high-radiation areas and their attenuation through barriers, labyrinths, and ducts. In the absence of such information, the shielding surrounding many types of accelerator facilities has generally been overdesigned. In some cases, however, inadequate shielding has been provided because the radiation profile of a particular accelerator with respect to energy spectrum, intensity, and species has not been thoroughly appreciated.

In this paper, various sources of radiation from small accelerators are described, in the light of the increasingly diverse applications that are being developed for research, medicine, and industry. Details of actual and hypothetical small accelerator facilities are discussed, to emphasize the necessity for thorough shielding-design study.

Before embarking on these relevant subjects, however, it is important to outline the kinds of accelerators and their applications, that are included in the scope of this paper.

1.1 Low-Energy Accelerators:

The term "low-energy accelerators" requires a definition. In comparison to the large synchrotons and linear accelerators that produce particle energies in the GeV realm, all accelerators are small. At the other extreme, all accelerators are large in comparison with the compact sealed neutron sources that generate 150-keV deuterons. In this paper, the term "low-energy" applies to all accelerators below 100 MeV in rating, that generate sufficient particle energy either to be brought out into the atmosphere or to instigate a nuclear reaction. Thus, electron accelerators with external 200-keV beams and 100-keV deuteron accelerators set somewhat arbitrary lower limits to the scope.

Within this broad energy range, there are a dozen different kinds of accelerators that provide a variety of particle energies, intensities, and species. Depending on their principles of operation, these accelerators can produce secondary radiations from more than one location. The direct or "potential-drop" types of machines can optionally accelerate charged particles of either polarity, sometimes simultaneously, thus further complicating the secondary-radiation situation.

Accelerators in this energy range are broadly distributed throughout the world. There are about 2000 machines in operation or under construction, with more than half of them in the United States. The majority are commercially manufactured, and about two-third of them are used in applications other than nuclear science and engineering.

1.2 Accelerator Applications:

When the present and contemplated applications for small accelerators are brought into consideration, all types of basic nuclear radiations are found to be useful, in one way or another. Table I summarizes the more important applications and the charged particles or secondary radiations of greatest interest.

Table I

Application	Electrons	X-Rays	Ions	Neutrons
Therapy	●	●	●	(●)
Radiography		●		●
Processing	●	(●)		
Activation			(●)	●
Research				
Atomic & Solid State	●		●	(●)
Chemistry & Biology	●	●	(●)	(●)
Nuclear	(●)	(●)	●	●
Neutron				●
Radiation effects	●	●	●	●

With some accelerator types, other radiations are simultaneously produced than those that are of direct value. The shielding designer must therefore be prepared to contend with fluences of electrons, ions, x-ray, neutrons, and (possibly) radiations from induced radioactivity. In some instances, he may be required to consider all of these different kinds of radiation in a single facility.

The design of shielded facilities for accelerators depends not only on the physical size of the machine and its auxiliary equipment, but also on the specific application for which the machine is to be used. In some instances, the accelerator and its high-radiation region can be completely separated, by shielded door or protective labyrinth barrier. Therapy installations and certain types of radiation-research facilities are included in this simple concept. To an increasing degree, however, facilities are being designed with multiple access, for material as well as for personnel, thereby requiring more stringent precautions regarding interlocks and warnings, on the one hand, and radiation attenuation through the apertures, on the other hand. Activation analysis, radiation processing, radiography -- all require the continual or frequent transfer of material through doorways, labyrinths, tunnels, or tubes.

Excluding for the moment those complex nuclear-research facilities that have a multiplicity of experimental areas, the facility for low-energy accelerators can be classified generally as either small and unipurposeful, or moderate in size for more versatile application. Either type of facility may require material flow of one kind or another. The multiportal research facility can be considered as a number of moderate-sized and separated high-radiation areas, with an additional complication of ensuring that the accelerated beam cannot be deflected into an area where radiation workers have been assigned to work.

1.3 Objectives in the Use of Accelerators:

The fundamental objective of the use of accelerator-produced radiations -- whether for research, medicine, or industrial application -- is to obtain important information concerning the intereactions of radiations with matter, or to effect changes in matter by means of these radiations. In many applications, this objective can be attained only through the purposeful production of high radiation intensities. In some cases, the kind of radiation may be selected from day to day, or the position of the source of radiation may be periodically changed.

In any event, this fundamental objective must be conditioned by the necessity of ensuring that all radiations from all possible sources within the accelerator facility are attenuated to levels consistent with radiation protection standards for both radiation workers and the general population.

2. SOURCES OF RADIATION

This review of the sources of radiations from low-energy accelerators is included only to emphasize the need for detailed practical information concerning their attenuation and scattering characteristics. The fundamental physical phenomena associated with these radiations are well understood, but the experimental data for specific reactions, spectra, and angular distributions are scattered and often ambiguous. Furthermore, the radiation profiles from individual types of accelerators are often unavailable, so that it becomes difficult to realistically estimate specific shielding requirements.

2.1 Primary Radiations:

The accelerated charged particles constitute the primary radiations of accelerators. In many applications, these particles never leave the vacuum region of an accelerator and consequently they do not *per se* contribute to the radiation hazards. The ranges in matter of charged particles from low-energy accelerators are finite and relatively short, as compared with the thicknesses needed to attenuate electromagnetic or neutron radiations. Targets or beam stoppers can be readily designed with adequate thickness to absorb these beams of charged particles.

In some applications, the charged particles are desirably brought out of the vacuum region through thin metallic-foil "windows", for the irradiation of materials that cannot or should not be introduced into the vacuum region. The charged particles can now be scattered by the atmosphere and materials in the vicinity of the particle beam. Ion beams constitute less of a problem than electron beams because of their very short ranges, even in air, at low energies.

Electron beams scatter prolifically in the atmosphere, and they create x-rays (bremsstrahlung) wherever they impinge on materials. For very low-energy systems, the scattering of electrons can be contained in reasonable dimensions, by appropriate labyrinths or by weatherstripped doors. At higher energies, the situation becomes more complex and cannot be resolved by such simple methods. Labyrinth or duct designs have to be more elaborate and space-consuming. The efficiency of producing x-rays increases with electron energy. Furthermore, the variety of nuclear reactions that can be instigated by electrons also increases with electron energy, as well as the attendant hazards from neutrons and induced radioactivity.

2.2 Secondary Radiations:

X-Rays from electron impingement, and neutrons from either electron or ion impingement constitute the important secondary radiations that can be produced from low-energy accelerators. (The radiations from induced radioactivity are discussed later). The fundamental attenuation characteristics of these radiations are well known, particularly with respect to monoenergetic beams. On the other hand, the scattering of neutrons through a room or within a labyrinth is less understood than the corresponding scattering of x-rays.

Engineering data are needed on the scattering and attenuation characteristics of actual x-ray and neutron spectra that are generated from thick targets or from nuclear reactions in which groups of neutron energies are produced. The trends of these characteristics with respect to angle, energy, nuclear reaction -- all are needed to provide a more clear-cut basis for shielding design. In the absence of such engineering information, it is necessary to apply the characteristics pertaining to the highest radiation energy involved in a particular case, or to engage in a series of complex (and often unsatisfying) computations. It is hazardous to presume some median "equivalent" energy for shielding design.

Individual judgment is often brought to bear on specific facility designs, in the form of limiting the choices of particles or nuclear reactions to be utilized in a particular program, whether in research, medicine, or industry. Often, this judgment is introduced in an effort to reduce the overall costs of shielding. The magnitude of the risk associated with this judgment depends on the inherent performance capabilities of the accelerator in question. Examples are given below.

a. In an atomic-physics laboratory, low-intensity beams of heavy-ion species only are produced from a small direct accelerator. The x-rays from back-streaming electrons constitute the sole radiation hazard, and they are readily attenuated by a few millimeters of lead. If deuterons were to be accelerated by this small accelerator, however, the resulting neutron fluences would require more than 4 feet of ordinaly concrete shielding. Except for mutual understanding among the research workers, there is no impediment to the introduction of deuterium gas into the ion source, and to the operation of the machine at much higher beam intensity than is customary in this laboratory.

b. The shielding of an accelerator for electron processing is designed on the basis that the electrons would impinge only on materials of low atomic number. If, at some later time, it becomes desirable to experiment with back-electron scattering from materials of high atomic number, such as tungsten or lead, this shielding might become marginal or inadequate because of the relatively high x-ray fluences.

It is all too easy (but often expensive, awkward, and space-consuming) to require a shielding design that is adequate for any conceivable kind and intensity of radiation that can be produced from a particular accelerator. It is more difficult to insist that a radiation survey be mde when the operating characteristics of an accelerator are changed, to ensure that the shielding design is still adequate. It is probably impractical to presume that continuing discipline and indoctrination of the radiation workers, whether long in service or recently introduced, could be satisfactorily maintained to avoid risks of the kind described in the examples above.

2.3 Other Sources of Radiation:

Aside from the accelerated particles and the secondary radiations they produce by intentional impingement on targets, there are several possible sources of radiations that sometimes depend on the principles of operation of an accelerator. For example, all direct ion accelerators, regardless of the magnitude of the high voltage, generate a stream of electrons directed toward the high-voltage terminal. Electron suppressors have been variously introduced to inhibit this back-streaming, but not to its complete elimination. The resulting x-rays, produced when the electrons impinge on materials in the anode region of the acceleration tube, must be considered in the shielding design. The character and intensity of these x-rays depends not only on the magnitude of the accelerating voltage, but also on the ion-beam species and intensity, tube-electrode design, vacuum conditions -- to name a few variables. The data relating to the x-rays produced by the back-streaming phenomenon are sparse and sometimes conflicting.

In tandem accelerators, these x-rays are produced in the midterminal region. Furthermore, neutrons can be produced in the same region, by the interaction of the negative ions accelerated from ground potential with the materials of the stripping agency that converts the ions from negative to positive charge for re-acceleration back to ground potential. The magnitude of the neutron flux depends on the accelerating voltage, the particle spacies and intensity, the stripper material, and the optical characteristics of the negative-ion beam. Under good operating conditions, the neutron flux might be considerably less intense than when the ion beam is misaligned or diffused by poor vacuum conditions. The attenuation characteristics of these neutrons must be presumed at present, in the absence of reproducible data in terms of neutron spectra and neutron flux. Terms such as "rem per hour", that yield no guidance concerning the quality factor of neutrons, are not especially helpful in attenuation considerations.

Induced radioactivity does not often influence the shielding design of an accelerator facility, particularly with the lower energy machines in our scope of interest. Depending on the particle species, its energy and intensity, and the interposed target material, almost every type of accelerator can be used to produce some kind of induced radioactivity. The magnitude of the radiation hazard, usually within the shielded area, must therefore be evaluated for specific facilities, to determine appropriate monitoring, handling and storage procedures.

Among the accelerator types most likely to produce radioactivity are the following:

All deuteron accelerators, regardless of energy;
Ion accelerators above a few MeV;
Electron accelerators above 10 MeV.

Less likely are those accelerators with insufficient particle energy to instigate many nuclear reactions, such as the following:

Electron accelerators between 1.67 and 10 MeV
(limited mainly to the photodisintegration of
beryllium and deuterium),

Ion accelerators below 2 MeV (limited mainly to
p,γ reactions).

In certain accelerator applications, radioactivity is intentionally produced (as in activation analysis or in radioisotope production), the amounts of which can be readily estimated from the electrical parameters of the accelerator, and can be readily located in the accelerator target region. Among the higher energy accelerators, on the other hand, there is a probability of inducing radioactivity along the acceleration or beam-transport paths. There is little detailed knowledge concerning the magnitude, and decay characteristics of this form of induced radioactivity. From the standpoint of developing safety procedures, it would be valuable to have some estimate of the local radiation hazard in the vicinity of cyclotrons, tandem and powerful electron linear accelerators, and to be able to schedule the length of delay before entering a facility in which radioactivy had been induced throughout the accelerator.

There are other possible sources of secondary radiations associated with low-energy accelerators, that contribute to the shielding problem within the room where the machine is installed. These sources do not influence the general shielding design, but they may be operating while the accelerator is turned off. Such sources include low-voltage injectors and klystrons. In effect, these sources should be treated as small particle accelerators, and they should be shielded in the same sense, if radiation workers are expected to be in the area while they are functioning.

3. SHIELDING DESIGN PROBLEMS

Once the detailed radiation characteristics and profiles of a particular accelerator are known, the task of estimating shielding-barrier thicknesses is quite straight-forward. What complicates the situation, however, is the preferred arrangment of these barriers and the appropriate allowances for apertures and interferences in the shielding walls. This complication becomes increasingly severe with the increasing diversity of accelerator application, in areas that are contiguous to those available to the general population.

3.1 Site Planning:

The shielding design for a new, separate accelerator facility can often be developed with a minimum of interference from established population behavior patterns and the occupancy of the space directly surrounding the facility. If the new building provides for the accelerator to be installed below the grade, the design problem is even more simplified.

Many new accelerator facilities must be accommodated in existing buildings or in building design that include other functions. Space now becomes more precious, and serious effort is often devoted to minimize the bulk of the required shielding. In some cases, this special design effort has resulted in very expensive shielding. Many years ago, for example, a 2-MeV x-ray generator was installed in a second-story location within an existing hospital, to be associated with the remainder of the therapy facilities. The floor and ceiling had to include shielding, in addition to the walls. To conserve space, lead was used throughout, with a 9-inch-thick "carpet" and partial wall, to attenuate the useful collimated x-ray beam, and 1 - 2 inches of lead for the remaining walls and ceiling, to attenuate the stray and scattered radiation. The cost of this special shielding exceeded the cost of the x-ray generator !

The shielding barriers in an existing building can sometimes be reduced in thickness, by surrounding portions of the accelerator with sufficient lead to attenuate the secondary radiation closer to the source. Certain types of direct ion accelerators lend themselves to this approach, with respect to reducing the radiation intensity from back-streaming electrons. Whether this local-shielding approach provides a resultant benefit depends on whether neutrons are to be produced by such an accelerator, in which case the neutron scattering may present a more serious shielding-barrier problem than the x-rays. If this same accelerator is to be used for the acceleration of electrons (with the consequent generation of x-rays), the local shielding is of little avail, because the x-rays are produced elsewhere.

Compact neutron generators can be inserted in pits in the floor, if the facility is at ground level. The shielding plug over the opening to the pit represents the only design problem. Water pipes, electrical conduit, and pneumatic tubes can be introduced through the floor so that neutron leakage through these interferences can be virtually eliminated. This design approach is not so satisfactory in the case of a floor-mounted accelerator with a downward deflected beam into a neutron pit. When deuterons are to be accelerated, there must be assurance that the beam cannot be produced without the necessary deflection. Further, there must be assurance that stray deuterons cannot impinge anywhere along the beam line above the pit. Otherwise, shielding must be provided around the accelerator itself.

The use of electron accelerators for the production-line irradiation of materials occasionally requires some ingenuity in shielding design. In certain industrial processes, the electron treatment must be provided between two other steps in a continuous-flow process. It is often impractical in these cases to deflect the material flow into a shielded wing. Consequently, design effort must be concentrated on providing a protective accelerator facility that is either surrounded by an uncontrolled area generally available to technicians and maintenance men, or at least restricted to radiation workers. An alternative is a "block-house" design with apertures to permit the flow of material under the electron beam.

Radiographic inspection of thick weldments and bulky devices with supervoltage x-rays has, until recently, been confined to laboratories where radiation safety can be ensured, with proper shielding designs and appropriate procedures. Field use of supervoltage x-ray generators is now developing, after the successful examples set by the use of portable and mobile gamma-ray sources. As field-erected pressure vessels become more complex (e.g. in nuclear-power applications) and as the storage of large solid-propellant missiles becomes more important, the use of supervoltage x-rays with radiographic characteristics beyond those of currently available gamma-ray sources will be demanded in the field to an increasing extent. The shielding problems associated with the field use of supervoltage x-ray generators far transcends those associated with conventional portable x-ray machines, that have been in field use for decades. Distance from the source is an important parameter of radiation attenuation, but discipline among unacquainted workers (and perhaps their supervisors) may become even more important. Protection for the radiographic-inspection team must also be provided. The need for this type of inspection is not questioned, but the solution to the radiation shielding problem is neither simple nor well controllable.

3 2. Apertures and Interferences:

In any accelerator facility, there must be access for personnel to enter and for apparatus to be moved in. These access portals must of course be designed so that radiation workers are protected from the radiations generated within the facility. The simplest means of meeting this requirement is to provide an interlocked door, either hinged, rotating, or rolling. The design of the door must include a shielding thickness equivalent to the adjacent walls. Furthermore, there must be sufficient overlap, on the radiation side of the portal, to ensure against leakage of radiation around the edges of the door, at the sides, top, and bottom. The mass of such a door usually is so great that a mechanical, hydraulic, or pneumatic system is required to move it routinely. On the other hand, the door must be manually movable from the inside, unless there is an alternate exit for personnel inadvertently caught inside a radiation enclosure.

Labyrinths are often used to shield against the radiations from an access portal. The radiations are attenuated in a labyrinth not only by the inverse square law but also by a series of scattering processes. Detailed knowledge about effective labyrinth design is sparse, and generally limited to x-ray installations below a few MeV in energy. Furthermore, labyrinths tend to become space-consuming for higher energy machines, and intentionally overdesigned because of lack of experimental information concerning their attenuation features. One additional disadvantage to a labyrinth is the difficulty of moving apparatus into the radiation area.

Ducts and tunnels are form of labyrinths, with the purpose of ventilating the radiation room or for conveying a flow of material into the room, e.g. for radiation processing. Small packages, trays, and flexible materials can be conveyed through specially designed mazes, using conventional materials-handling techniques. Fluids can be piped into the radiation area with gradual offsets to provide labyrinth-like shielding. Bulky materials ~~or~~ large inflexible panels may have to be conveyed through tunnels that are longer than the range of the electrons, that are narrow enough to provide sufficient radiation attenuation, and that are constructed so they can be serviced in the event of conveyor failure.

3.3 Special Shielding Problems:

In quite a few accelerator facilities that are incorporated into a separate building or a special wing, the roof is designed with little if any shielding, on the grounds that the upward-directed radiations would be scattered and attenuated in the atmosphere above the building. Two problems present themselves: (1) the possibility of causing excessive radiation fluence in adjacent buildings that are in the line of sight with the unshielded radiation source; (2) back-scattering of the radiation from the atmosphere, or "sky-shine".

The first problem can be solved by constructing the shielding of the walls high enough to prevent the direct, unattenuated radiation from illuminating adjacent buildings. If necessary, shielding in the ceiling (or roof) may be required. The second problem is not as readily solved, because there is not sufficient experimental information concerning sky-shine and its relative contribution to the immediate environment of an accelerator facility. Back-scattering of the radiations from the material of the roof also cannot be completely ignored. In one 2-MeV radiographic facility in the Northeast, the back-scattered radiation from the roof to the area immediately surrounding the building increased by a factor of approximately 5 with a 2-foot snow load on the roof.

Detachable or temporary shielding around a radiation source can cause radiation-safety hazard, if the facility is not protective without the local shielding. Certain accelerator designs include an interlocking arrangement, to open the control circuit in the event that the local shielding is removed. Completely self-shielded electron-processing equipment has been designed with this safety feature in mind. On the other hand, supervoltage radiographic equipment is often used with its x-ray collimating shield removed, to permit circumferential radiography. In such installations, the shielding-wall thicknesses are designed to attenuate the uncollimated beam.

The targets of neutron generators are occasionally surrounded with neutron-moderating material, such as paraffin, polyethylene, or water. These materials also serve to attenuate the neutron flux. Without some interlocking arrangement with the accelerator controls, however, it would be hazardous to depend on this form of local shielding in designing the radiation barriers for the entire facility.

4. CONCLUDING REMARKS:

Several observations can be made from this dissertation on the radiation-shielding problem with low-energy accelerators.

a. There are probably 2000 accelerators throughout the world with adequate shielding, however their facility designs were developed.

b. Remarkably little quantitative information is available concerning the overall effectiveness and efficiency of design of these existing facilities.

c. Despite the quantities of different types of accelerators currently in use, there is inadequate or at least controversial information relating to their radiation characteristics and profiles.

d. There have been countless computations of the radiation-attenuation characteristics of materials, labyrinths, and ducts, but relatively few experimental investigations with actual radiation spectra and angular distributions from the more important radiation-producing reactions.

As the applications for low-energy accelerators become more diverse, and as the numbers of accelerators increase, there will be a more and more pressing need for quantitative information to develop realistic shielding designs.

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PRACTICAL RADIATION PROTECTION MEASUREMENTS

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"Practical Radiation Protection Measurements"

Practical radiation protection measurements around small accelerators are made with almost the same instruments that are used to make radiation protection measurements around large accelerators. The regulatory agencies that require you to maintain personnel exposure records do not discriminate against you in any way because of the energy of your accelerator. The Maximum Permissible Cumulative Exposure formula, D=5(N-18), is not a function of energy. In fact, they do not even attempt to recommend the type of device you use for personnel monitoring, but once you specify the technique you anticipate using, they may ask you to explain the details of your calibration technique. Around high energy accelerators this is much more difficult than it is around low energy accelerators. A good deal of information is available regarding calibration for dose measurement at the lower energies and instrumentation for making these measurements are readily available from commercial instrument manufacturers.

The variety of applications of small accelerators would require the user to have the capability of measuring all types of radiation, however, the ability to measure electrons (betas), X and gamma rays and slow, intermediate and fast neutrons are the most important types of radiation one encounters.

Let us consider the types of measurements required during the two modes of operation of an accelerator: (1) Shut-down or maintenance period, and (2) Operating period.

Shut-down Period

During the shut-down or maintenance period there are two major areas that require practical measurements. These are activation of machine components and handling of radioactive targets.

Let us consider activation of machine components first. For some accelerators this may be the most important area as far as personnel exposures are concerned. Any maintenance on the machine must be controlled in such a manner so that the weekly or quarterly exposures are not exceeded. This could be a serious problem with a machine that has to be shut down for repairs more frequently. The maintenance personnel staff may have to be increased beyond its functional size in order to get the machine operating.

The types of instruments for measuring radiation from activated components is fairly standard. One can use ionization chambers, like Cutie Pies that are sensitive to both electrons and gamma rays or ionization chambers like the old type Junos that have adjustable windows for stopping the electrons. Using this technique, one can get a ratio of the total skin dose to the penetrating whole body exposure. The regulations specify different permissible levels for skin dose and whole body dose. Film badges and TLD devices can give the same kind of information but with some element of time delay involved. TLD devices may have a shorter time delay than film badges and one is able to use these to make measurements in areas of concern and then specify the working time in these areas. Pocket ion chambers or direct reading pocket dosimeters can also be utilized to provide one with information necessary for controlling exposures to levels specified by the controlling regulatory agency. Another important type of measurement that is necessary in maintenance is that of removing activated parts for repairs or modifications. The part removed should be surveyed and working times with this part assigned in accordance with permissible exposure levels. Any machining or handling of these parts which could result in the removal of any activity should be controlled and handled as radioactive waste. After any of these operations are performed wipe tests of the area and equipment should be performed. These wipe tests can be counted in one of several ways. They can be counted in a shielded end-window G. M. counter or proportional 2 Pi counter connected to a scaler or by a shielded NaI scintillation crystal connected to a multi-channel analyzer. The latter technique may be useful in identifying the build-up of long-lived isotopes.

The second area requiring practical measurements during shut-down of small accelerators is the wide spread use of tritium targets. Due to the low energy of the electron emitted from tritium and the fact that it can come off the target in a gaseous form makes it very difficult to measure. There are a few commercially available instruments for making these types of surveys.

Internal contamination can be evaluated by wipe tests of the inside wall of the accelerator tube and target assembly areas. These wipes can be evaluated for gross contamination with 2 Pi counters or thin end-window G. M. tubes. Oil from vacuum pumps can be counted with liquid scintillation counters.

The release of tritium in the gaseous state can be evaluated by using large volume ionization chambers which circulate the air through the ionization chamber. These types of chambers require micro-micro ammeters or vibrating Reed electrometers to measure levels near the maximum permissible concentrations of tritium in air.

A tolerance concentration of tritium, $5X10^{-6}$uc/ml, with an average energy of 6 kev in a one liter chamber will yield an ionization current of approximately 10^{-15} amperes. With the electrometer sensitivity set at 10^{-13} amperes full scale, one gets a reading of about 1% of full scale. The continuous average background readings can be about 1 or 2% of full scale with some fluctuations of the same order. In addition, any other sources of radiation in the area will cause ionization currents within the chamber. These currents cannot be distinguished from those caused by the tritium. This type of mon itor can be used when changing targets or for monitoring the ventilation stack or storage area. New or used tritium targets should be stored in a hood or in a well-ventilated area, since there is always some outgassing of the tritium. Personnel monitoring can be performed by radio-bioassay of urine samples.

Operating Period

If a small accelerator is properly shielded, then the practical radiation measurements around the machine are simple. Low levels of gamma radiation and small fluxes of neutrons of low energy are the types of radiation you will encounter. Even Geiger counters with audible and visual indicators can be used as area monitors to indicate relative intensities. Film badges, pocket chambers, direct reading dosimeters, and TLD devices are all quite satisfactory personnel monitoring devices. Film badges for monitoring neurtons, which, at a properly shielded accelerator, will be predominantly in the low energy region, are not very satisfactory. The production of tracks by proton recoils has a threshhold somewhere above 1/2 Mev. Thermal neutrons interact with the nitrogen in the emulsion of the films (${}_7N^{14} + {}_0n^1 \qquad {}_1P^1 + {}_0C^{13}$) giving off a proton which produces a track in the developed film. The Q of this reaction is quite low and the length of the track is short compared to the tracks produced in the emulsion by proton recoils from fast neutrons. The cross section for this reaction is 1.8 barns, however, the number of nitrogen atoms in the emulsion is quite small. Although this interaction could occur with a nitrogen atom in the air directly in front of the open window, a tolerance flux of 670 $n/cm^2/sec$ is probably not detectable. A technique used by some film badge companies is to look at the density produced on the beta-gamma sensitive film by the activation of the cadmium filter. High fluxes of slow neutrons are not usually found on the outside of properly shielded small accelerators.

Fluxes of intermediate and fast neutrons are usually quite low. These low fluxes of neutrons are not very easily detectable by neutron track emulsions used in film badges as a technique for personnel monitoring.

Even at higher fluxes, when the emulsion may be useful, there is a problem of "track fading." The period that the badge is worn must be short or the latent image fades. The cost versus the results of this type of personnel monitoring is debatable. Pocket chambers, direct reading dosimeters and TLD devices are not yet developed sufficiently to provide satisfactory monitoring in this area of neutron dosimetry.

The best technique for this type of monitoring is using one of a variety of neutron survey instruments. There are a variety of neutron instruments commercially available to monitor the slow, intermediate and fast neutrons.

Slow neutrons: $B^{10}F_3$ tubes and Li^6I crystals are quite satisfactory. The only major problem is to get from the manufacturer the details necessary for calibration of the detector. You must know the actual amount of B-10 in the BF_3 tube or the Li-6 in the LiI crystal. Then you can convert the dpm or cpm indicated by the detector to a flux number. If you cannot obtain this information then you can use foil activation techniques. A variety of accurately weighed foils are commercially available for this purpose. A neutron howitzer is usually used to irradiate the foils and then they are counted. A variety of devices can be used to count these foils. Two or four Pi proportional counters, NaI crystals with single channel or multi-channel analyzers or even Geiger-Muller tubes whose geometry, backscatter and efficiencey are known for the energy of the emitted radiation. Elaborate coincidence counting set-ups can be used for activated foils that decay by emitting positrons.

Intermediate and Fast neutrons: Intermediate and fast neutron detectors usually operate on the same principal as slow neutron detectors except that the detector is surrounded by some moderating material. The thicker the moderator surrounding the detector the more sensitive it is to the higher energy neutron. Some commercially available detectors with 9 to 10 inches of a polyethylene as a moderator surrounding the detector, read out the dose in millirems per hour. Calibration curves for these detectors indicate that they follow the RBE curve up to about 7 or 8 Mev neutrons. Their response is usually a little high in the intermediate energy region or a little low in the higher energy region. These instruments are calibrated with readily available neutron sources such as RaBe, PuBe, and AmBe. The average neutron energy of these sources is around 4 or 5 Mev.

For surveying around the outside of shielded small accelerators these detectors are quite satisfactory, even when using a tritium target to get the 14 Mev neutrons. By the time these high energy neutrons penetrate the shielding they have lost sufficient energy so that they are in the calibrated energy spectrum of the detector. These detectors are quite insensitive to gamma doses up to several rems, however, they should be checked out by exposing them to Ra or Co^{60} gamma rays. A discriminator adjustment is usually quite accessible for setting the signal level at a point well above the gamma level without rejecting any of the neutron pulses.

Another type of neutron monitor which is useful utilizes the principle of proton recoils. This detector, a proportional counter, is filled with methane and argon. The inner wall is lined with polyethylene. The polyethylene lining is the source of the proton recoils.

Calibration: In the energy region of the readily available neutron sources, especially the PuBe neutron source, one can obtain results well within a factor of 2 from film badges and some of these commercially available instruments.

Since these neutron sources are not small in size (about 1" diameter and 2" long), one cannot calculate the flux at a distance assuming a point source. One finds that you must start taking readings at about 12". At that distance you are down to about 100 neutrons/cm^2/second. If you use the inverse square rule to calculate the dose, the calculated values agree satisfactorily with the measured dose rate using film badges and commercially available instruments.

The moderated slow neutron detectors can be calibrated to give the relative neutron intensity from tritium targets. This can be done by one of two methods. (1) By increasing the thickness of moderator surrounding the detector, and(2) By irradiating materials with known cross-sections for 14 Mev neutrons. Several materials are available. Natural copper is an extremely useful material for calibration of 14 Mev neutrons. Copper, which has an abundance of 70% of Cu^{63}, and 30% of Cu^{65}, is a useful material. It has a cross-section of 0.55 barns for the (n, 2n) reaction which yield Cu^{62} a positron emitter with a half-life of 9.9 minutes. The Cu^{65} has a (n, p) reaction about 25 times smaller than the (n, 2n) reaction in Cu^{63} yielding Ni^{65} which is not a positron emitter and a (n, 2n) reaction which is about 2 times larger than the (n, 2n) reaction in Cu^{63}. This reaction in Cu^{65} yields Cu^{64} which is also a positron emitter. However, if you irradiate for a period of only a few minutes, then the amount of the longer lived Cu^{64} positron emitter is negligible.

If one sets up an anti-coincidence counting set-up with a calibrated Na^{22} source for the 0.51 mev annilation gamma ray, then one can calculate the flux at the detector using the inverse square law, and calibrate the detector reading for the 14 Mev flux. As long as one does not change the shielding configuration so that the scattered contribution remains relatively constant, one can use the detector to evaluate the condition of the tritium target without going through the rigor of foil activation and anti-coincidence counting each time.

In conclusion, I would like to state that the above information applies to properly shielded small accelerators. When the accelerators can not be or are not properly shielded, then this information can be, I believe, helpful in evaluating the conditions and setting up work limits or time schedules so that the facility can operate within the exposure limitation set up by the regulatory agencies.

Many other techniques can be utilized to perform the same measurements, but usually they are more elaborate and time consuming. In addition one's own ingenuity can always improve on these types of measurements. In that case, I would be glad to hear from you.

A SOLUTION TO TRITIUM PUMP CONTAMINATION FOR SMALL ACCELERATORS

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ABSTRACT

Tritium contamination has been of constant concern to the investigator using a small accelerator as an intense neutron source. The usual vacuum system associated with a small accelerator consists of a mechanical roughing pump and an oil diffusion or getter-ion pump. Problems arise because (1) the diffusion pump will exhaust tritium to the surrounding area through the roughing pump, and (2) after prolonged pumping of tritium the getter-ion pump will become unstable necessitating the changing or cleaning of its elements accompanied by a release of tritium. A solution is suggested which, by the separation of the static (beam OFF) and dynamic (beam on) pumping functions and the incorporation of a titanium bulk sublimator into the vacuum system, should allow a maintainence-free pump life of at least ten years. The system permanently buries tritium in the pump chamber walls thus greatly reducing the problem of uncontrolled tritium release.

INTRODUCTION

The requirement for a high neutron yield has led many investigators to use the $T(d, n)He^4$ reaction. Because tritium decays by beta emission, with a half-life of over 12 years, system contamination can prove to be a biological hazard.[1] The work presented here was performed in the development of a small 300 kilovolt, 15 milliampere positive ion accelerator designed primarily for the production of neutrons.* Since both high gas loads and tritium targets would be involved, pumping speed and minimum maintenance were prime requirements of the vacuum system.

Several pump configurations were considered before a satisfactory system was evolved. The use of an oil diffusion pump introduced the possibility of hydrocarbon contamination of the target, low pumping speed to volume ratio, possible tritium contamination of the oil and the necessity of a cryo-baffle. A getter-ion pump posed the problems of thermal instability[2] which results from reemission of absorbed deuterium or tritium, repair problems because of tritium contamination[3] and reduced lifetime because of high deuterium gas load requirements. These known pump difficulties combined with the fact that higher beam currents would only aggravate the problems, led to the separation of the static (beam off) and dynamic (beam on) pumping functions of the vacuum system.

Vacuum System

In figure 1 is shown a schematic of an accelerator vacuum system where a bank of molecular sieve sorption pumps and a getter-ion pump are used to maintain the static vacuum when the only gas load is surface degassing and residual leakage. Under a gas load to the ion source, the getter-ion pump is valved off from the system and the dynamic vacuum is maintained by a titanium sublimator and a small getter-ion appendage pump.

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* Constructed for NASA by Oak Ridge Technical Enterprises Corp.

The bulk sublimator is essentially a device containing a rod of titanium heated to 1500° F and sublimed on to the surface of a water cooled chamber. The fresh titanium forms stable solid compounds with the chemically active gas molecules that strike the surface, resulting in high pumping speeds.

Separation of the pumping functions has the following advantages:

1. Most of the tritium, either released from the target or resulting from mixed beam operation, will be contained in the walls of the sublimator in the form of titanium tritide.

2. The getter-ion pumps used in the system should have a maintenance free life in excess of 50,000 hours since they will normally be operating in the 1×10^{-7} torr range.

3. The bulk sublimator should have a maintenance free life in excess of 20,000 hours (based on a hydrogen gas load of 10 atm. $\text{cm.}^3/\text{hr.}$) before replacement of the titanium rod is required.

4. High pumping speed is available for active gases.

5. Tritium is permanently buried in the walls of the sublimator and does not pose an outgassing problem.

6. The sublimator provides considerable pumping speed in the 1×10^{-4} to 2×10^{-2} torr range where start-up can be difficult for a getter-ion pump alone.

OPERATING EXPERIENCE

A 300 kilovolt, accelerator, incorporating static and dynamic pumping has been in operation for the past 6 months. Beam currents up to 30 milliamperes have been obtained, although the accelerator is normally operated at 13 milliamperes. Figure 2 shows the accelerator with the beam tube entering a 6 ft. diameter water tank. The accelerator is small, being just eight feet from source to target. The sublimator and three sorption pumps are mounted on the right side of the main manifold and the getter-ion pump is mounted on the left side of the manifold. The vacuum system has a volume of about 300 liters and is maintained in a static condition at 7×10^{-8} torr by a 270 liter/sec. getter-ion pump and the residual sublimator film. Rough pumping is provided by the 3 sorption pumps. Under a gas load the vacuum is maintained by a titanium sublimator and a small 10 liter/sec. getter-ion pump, the 270 liter getter-ion pump being valved off from the system. Figure 3 shows the vacuum as a function of time for a typical pumpdown and operating cycle. Considerable difficulty had been experienced in starting the getter-ion pump in the 1×10^{-3} torr range. Usually 3 sorption pumps and 3 hours were required. As can be seen in figure 3 this mode of operation was changed by the discovery that (contrary to the manufacturers statement that the pump must not be started above 1×10^{-4} torr) the sublimator could be started in the 1 to 2×10^{-2} torr range and would provide substantial pumping where it was most needed. This pump has been subsequently started many times in this range, however, and there has never been a glow discharge or arcing problem. The vacuum system routinely goes from atmosphere to 5×10^{-7} torr in one hour.

As can be seen from figure 3 a layer of titanium put down in a half hour will permit operation for at least 8 hours, at 280 kilovolts and 13 milliamperes. The titanium layer pumps the active gases and the 10 liter/sec ion pump takes care of the hydrocarbons and inactive gas load. The 10 liter/sec pump is placed as an appendage on the sublimator chamber. Thus, the titanium layer effectively screens out the deuterium gas load to the ion pump preventing pump deterioration from high deuterium gas loads, and provides a pump life comparable to that of the 270 liter static pump. The sublimator chamber is approximately 27 inches long by 18 inches in diameter and is water cooled. For hydrogen the pumping speed is approximately 30,000 liters/sec. By using liquid nitrogen to cool the chamber, the speed can be increased to about 130,000 liters/sec. Figure 4 shows the sublimator titanium rod at operating temperature. Based on operation at 280 kilovolts and 13 milliamperes, the titanium rod should last for 20,000 hours before replacement. This estimate is based on running the sublimator in a cycling mode to obtain maximum utilization of the titanium. Thus the dynamic gas load will always be handled by a layer of titanium deposited on the sublimator chamber walls and the 10 liter/sec getter-ion pump.

CONCLUSION

Because of the trend toward higher beam currents, the problems associated with accelerator tritium contamination can only become more severe. The solution proposed will not only reduce the tritium release problem by safely storing it in the walls of the sublimator pump, but also provide the large pumping speed necessary for higher gas loads. The pumping speed for active gases for the 300 liter system can be varied from

100 to 130,000 liters/sec depending upon the need. It has been shown that by running the sublimator in a cyclic mode, in conjunction with a small getter-ion pump, long trouble free running can be expected.

Separation of the pump functions also suggests that in the design of future small accelerators it might be desirable to incorporate a titanium bulk sublimator directly into the pump manifold with an appropriate optical baffle to permit beam passage. This would produce extremely high pumping capacity where it is most useful and would also act as a restriction to the passage of target released tritium to the rest of the accelerator system.

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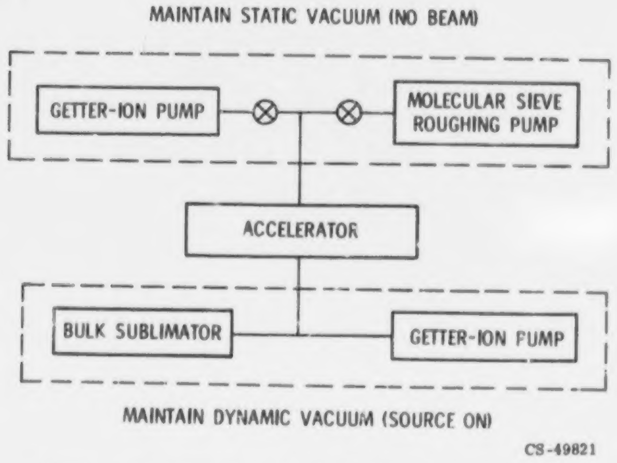
MAINTAIN STATIC VACUUM (NO BEAM)
GETTER-ION PUMP
MOLECULAR SIEVE ROUGHING PUMP
ACCELERATOR
BULK SUBLIMATOR
GETTER-ION PUMP
MAINTAIN DYNAMIC VACUUM (SOURCE ON)
CS-49821

Figure 1. - Schematic of pumping system for small accelerator.

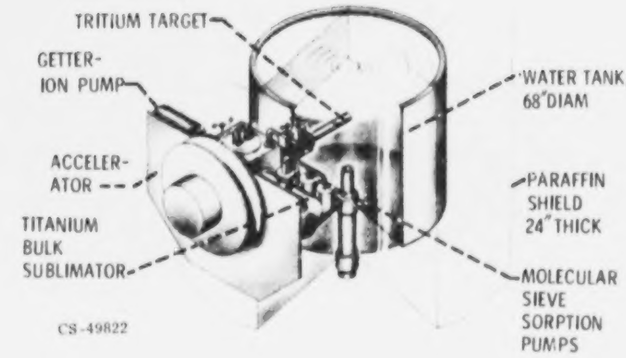
TRITIUM TARGET
GETTER-ION PUMP
ACCELERATOR
TITANIUM BULK SUBLIMATOR
WATER TANK, 68"DIAM
PARAFFIN SHIELD 24" THICK
MOLECULAR SIEVE SORPTION PUMPS
CS-49822

Figure 2. - 300 Kilovolt accelerator and water tank.

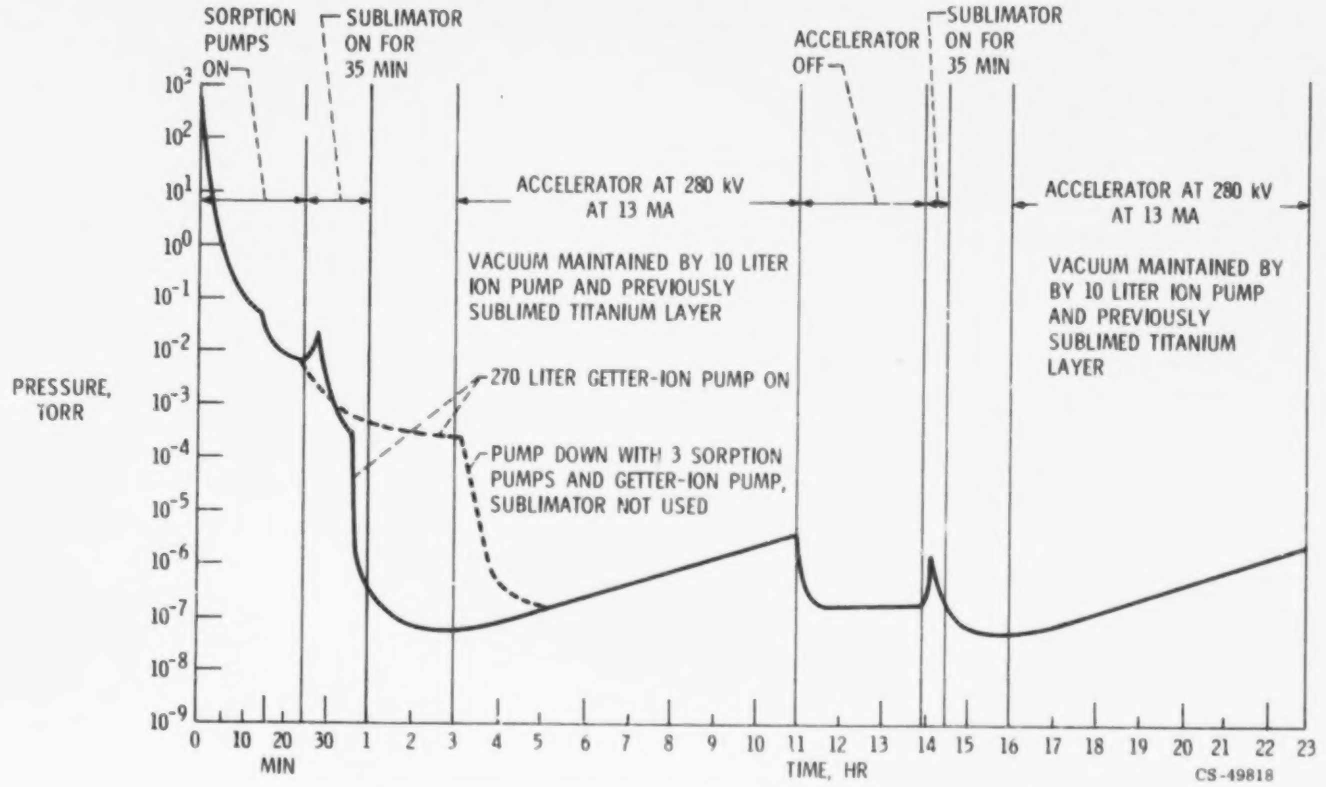

Figure 3. - Typical pumpdown and operating cycle for 300 kV accelerator. (Volume of system 300 liters.)

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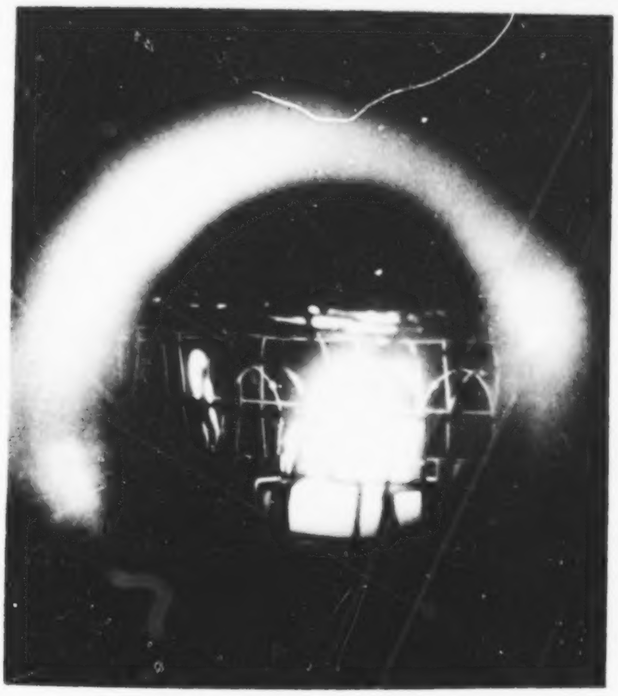

Figure 4. - Sublimator titanium rod at operating temperature.

USE OF COMPUTERS AT ACCELERATORS

by

J. F. Mollenauer
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Murray Hill, New Jersey 07974

ABSTRACT

In recent years the prices of small computers have become competitive with wired logic pulse height analyzers, and represent a small fraction of the cost of an accelerator installation. Even specialized data input interfacing can be handled by commercially-available modules. While computers introduce some complexity into an experiment, the results from their use have been very worthwhile. The advantages include convenient output format, flexibility, and the ability to monitor complex experiments efficiently. Man-computer interaction with displays and light pens has made data analysis quicker and more effective in many cases. Several examples of on line data analysis are given.

This work has been supported in part by equipment grants from the National Science Foundation at Rutgers, the State University.

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Introduction

There have been very few pieces of a research equipment ever developed that have had the quick and widespread acceptance accorded the digital computer. The extreme versatility of this tool makes it adaptable to a very wide variety of experiments in most fields of research.

Computers were used in accelerator laboratories as soon as they became cheap enough to compete with the most elaborate wired-program data-collection devices. The cost of multi-parameter wired logic devices was reaching upward to $100,000 in the early 1960's, when computers began to fall below this price range. Since that time computers have continued to become cheaper and have become competitive with a greater and greater fraction of the conventional pulse-height analyzers on the market. Since a general-purpose

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This work has been supported in part by equipment grants from the National Science Foundation at Rutgers, the State University.

computer can now be purchased for under $10,000 there are very few data collection tasks where a computer is not to be considered. This is not to say that it is always the best choice, but certainly it cannot be dismissed without careful consideration of whether its advantages do not outweigh any price disadvantage.

The economics of installing any research equipment, or production equipment in a factory, are most rationally judged on the basis of whether the incremental cost of the equipment is less than the incremental improvement in the quality or quantity of the work turned out. In research this is a much more subjective judgement than in industrial production but still a useful yardstick. Since this conference is devoted to small accelerators I will emphasize considerations pertinent to small systems. Granted some latitude in the fraction of capital budget that is devoted to data handling systems, it is still clear that the number of dollars justified at a small accelerator will be smaller than at a large one. If we say arbitrarily that 10 to 20 percent of the total, including salaries and amortization of building, accelerator, and ancillary apparatus, is reasonable for a computer system, then very few accelerators cannot justify the installation of a computer.

Mass Produced Interfaces

While quantity production of computers and their components has lowered the prices of central processors, special-purpose logic circuitry remains expensive. Although the integrated circuit logic elements are very cheap, design and debugging costs of data-input and display circuits are substantial since they are usually amortized over only one system.

A solution to this problem has been found by the major European nuclear laboratories. They have jointly published a specification for a standard digital module system known as Camac.[1] Within this system, commercial modules are available at modest cost. The system is computer-independent in the sense that only an adapter need be specially designed for any one type of computer; beyond the adapter the system is the same for all makes. Adapters are now available for several 12- and 16-bit computers. Typical interfacing costs for most laboratory work are held to a few thousand dollars with the Camac modules. While a standardized digital module system may not be fully optimized for an individual system, the cost advantage will more than compensate in most cases.

Complexity: The Negative Influence

The problem of complexity in a general purpose instrument is not solved as easily as that of cost by mass production economies. In fact, the very cheapness of integrated circuit logic encourages computer manufacturers to add complexity to central processors. Carefully handled, this complexity enables the user to get more out of his relatively expensive core memory and peripherals but places a barrier in the way of easy utilization.

An ancient rule of thumb in computer applications is that software cost over the life of a computer equals hardware cost. With computers becoming at once cheaper and more complex, the ratio is bound to shift toward higher software costs, most particularly in very small computers which cost less than a year's salary for a good programmer.

The only obvious answer to this difficulty lies in the sharing of software by substantial groups of users. Unfortunately there is little status gained by research personnel in submitting a program to a computer user's group, no matter how clever or useful the program is. A paper submitted to a journal, even if no one reads it, will do more for a scientific career than half a dozen programs submitted and actually used by others. The scarcity of useful programs in users group catalogs attests this.

One must therefore look to those who have somethink to gain by providing applications software, the suppliers of packaged systems. Here quantity production or group buying power does provide benefits. Some computer firms have added electronics to make nuclear physics packages while some electronics firms have added small computers to their electronics; both groups have added applications software. This software may not cover all experiments performed with the system, but it provides a much easier startup period than would otherwise exist.

In addition to the complexity inherent in any computer programming task, there are opportunities for escalation in abundance. The reasoning is seductive: let us expand the computer to handle experiment x which we could not otherwise do; since we have an expanded computer and experiment x is not always running, let us devote the excess capacity to the other operations when we are running experiments that do not use the system to capacity. Writing programs to do two things simultaneously is probably four times as hard as writing for one experiment, and the user is always haunted by the fear that the other experiment will distort or erase his data. This is an area to be approached with caution, and one that we at the Rutgers-Bell nuclear physics laboratory are just now approaching although we have had a computer for six years.

Computers for Data Acquisition

Despite the possible pitfalls there are still very great advantages of computer systems over any other data acquisition method. These might be summarized as follows:

1. Convenient output format.

At the very least a computer is capable of outputting the data it has collected in a format suitable for input to a larger computer for full analysis or printing, a vast advantage over non-computer-compatible readout systems. For this purpose teletype (ASR33 or ASR35)paper tape punches are not really fast enough to be very satisfactory, just as the teletype-speed paper tape input is agonizingly slow. It is wise to invest in a fast paper tape system or magnetic tape, budget permitting.

2. Flexibility.

A computer can be programmed to do a host of things that were not thought of when it was ordered. A user who is not stimulated to think of new applications for a computer once it has arrived in the laboratory is unimaginative indeed. For example, the computer may be reprogrammed to handle multiparameter data, or to apply selection criteria to input data before storing it, or to interact with the apparatus by moving a detector array.

3. Experiment monitoring.

Efficiency in using accelerator time is improved by gains in monitoring an experiment, particularly a complex one in which various drifts may be hard to catch by inspection of the raw data. The computer can do a partial analysis of the data on-line, permitting the experimenter to monitor the experiment and detect faults.

4. On-line control.

In addition to acting as a receptacle for data, the computer can apply feedback to the experiment, terminating runs when sufficient statistics have been obtained, positioning detectors and the like. If the situation is sufficently routine, this may make it possible for the experiment to be run without the presence of the experimenter.

Computers for Accelerator Control

Here the situation is far less positive than for data collection. Considerations of safety for equipment and personnel dictate the presence of one or two human operators at the accelerator. A large accelerator, from tandem van deGraaff size up, has too many potential trouble spots for inexpensive connection to a computer. If it were computerized fully enough to replace the human operators, the cost would exceed the saving in manpower. On the other hand, small accelerators can generally be operated by the experimenters, and the advantage of computerizing the accelerator might lie in permitting unattended overnight runs.

On very large accelerators, the control problem may be severe enough to require a computer to keep good beam characteristics, but human operators are still on duty at such machines for nonroutine operations and to correct troubles.

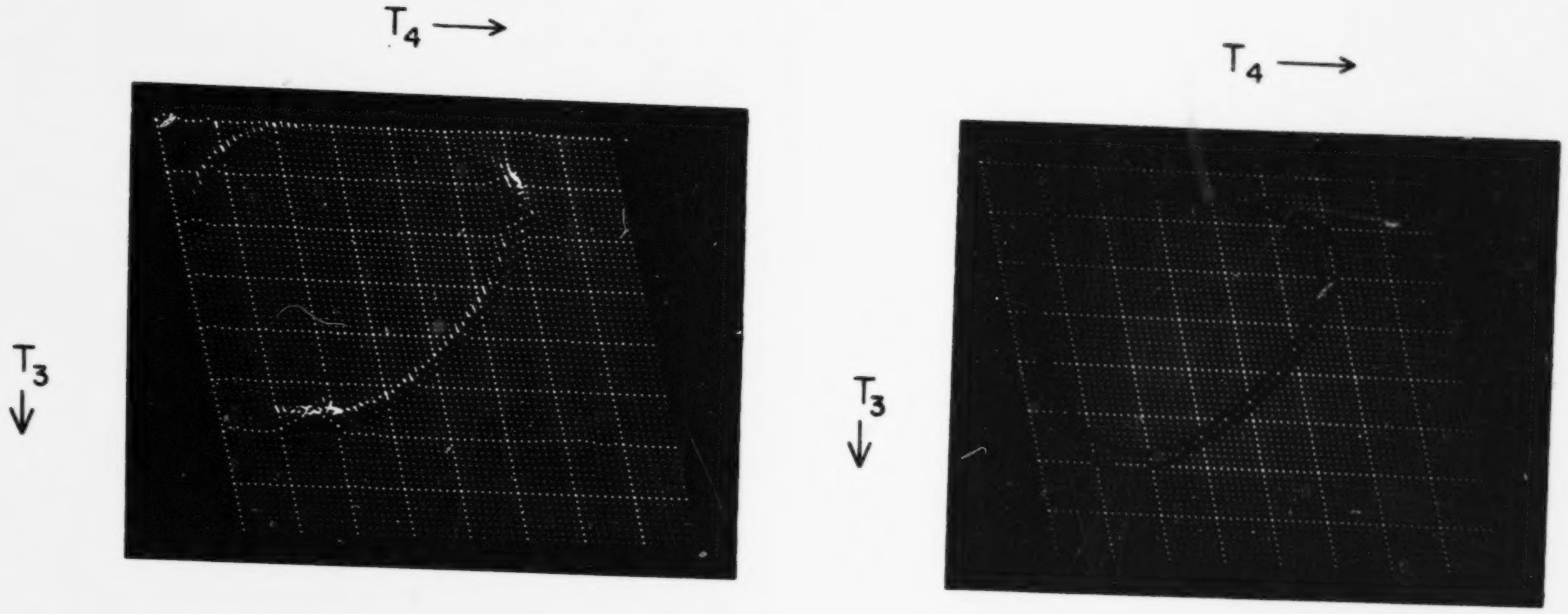
Applications at the Rutgers-Bell Tandem

The computer applications illustrated here were carried out on an SDS 910 and its sister machine, an SDS 925, which together represent considerable hardware. However, most of these applications could be approximated today on an 8K 16-bit computer equipped with interfaces for analog-to-digital converters and display scopes.

The first use to which the 910 was put was in two-particle coincidence experiments. The computer was able not only to store and display the number of events as a function of two variables, but also to calculate the locus of the allowed region for the reaction of interest. This is shown in Fig. 1. While a wired-logic analyzer could have been employed for the data acquisition, it could not have performed the calculation.

More extensive calculations have enabled us to predict the expected experimental yields as a function of the two energy parameters and to display the results in the same format as the data itself. By introducing Monte Carlo averaging over the target thickness and detector aperture, we have been able to optimize the experimental parameters for resolving given features of the data and differentiating between alternative models, as in Fig. 2. These calculations have been too extensive for the 910 and 925 and have been carried out at the computer center, with the results brought on magnetic tape for display and evaluation of independent terms in the theory.[2]

More conventional output of results may also be done on the scope as shown in Fig. 3. The histogram was drawn on the same cathode ray tube, and indicates the number of events along the kinematic line as a function of energy of one of the emerging particles. The data on the kinematic line were separated from the rest of background by use of a light pen. When the light pen detects



THE REACTION IS $1+2 \longrightarrow 3+4+5$

$D+P \longrightarrow P+P+N$

$T_1 = 21.1$ MeV $\theta_3 = 26.0°$ $\theta_4 = -26.0°$

ANGULAR WIDTHS OF DETECTORS = 2.5°

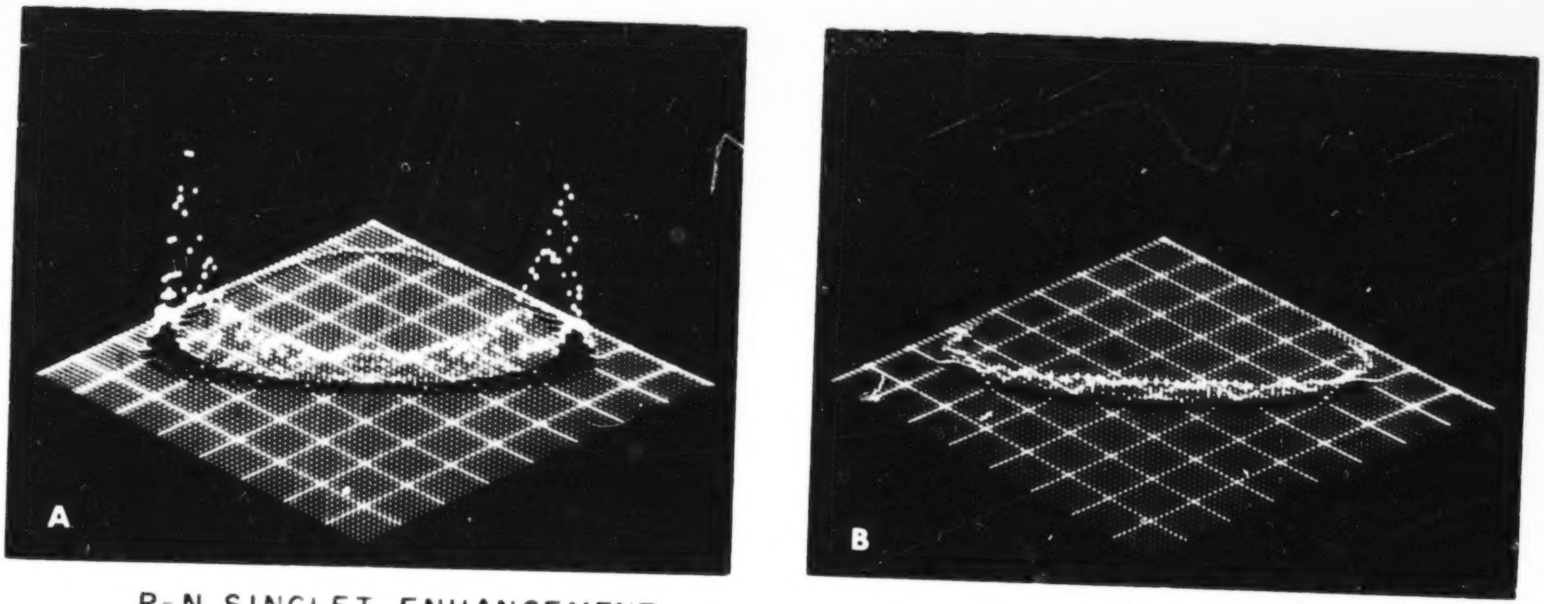
KINEMATICS CALCULATED FOR ANGULAR EXTREMES OF DETECTORS

12.0 MeV IN CHANNEL $x = y = 48$

RESONANCES DUE TO VIRTUAL SINGLET DEUTERONS AND VIRTUAL DIPROTON.

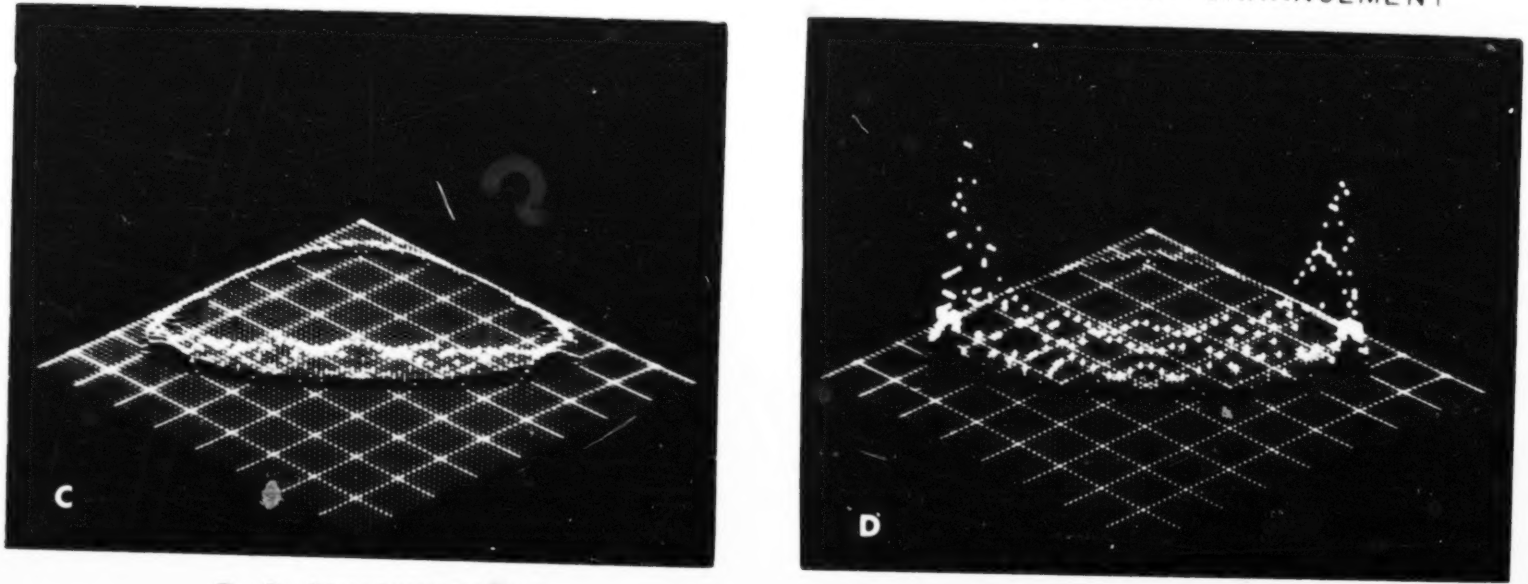
FIGURE 1. Comparison of actual data (left) with previously calculated kinematics, for a three-body-breakup reaction. T_3 and T_4 are the energies of the two emitted protons in $D+P \rightarrow P+P+N$.

D + P → P + P + N $E_D = 21.1$ MeV



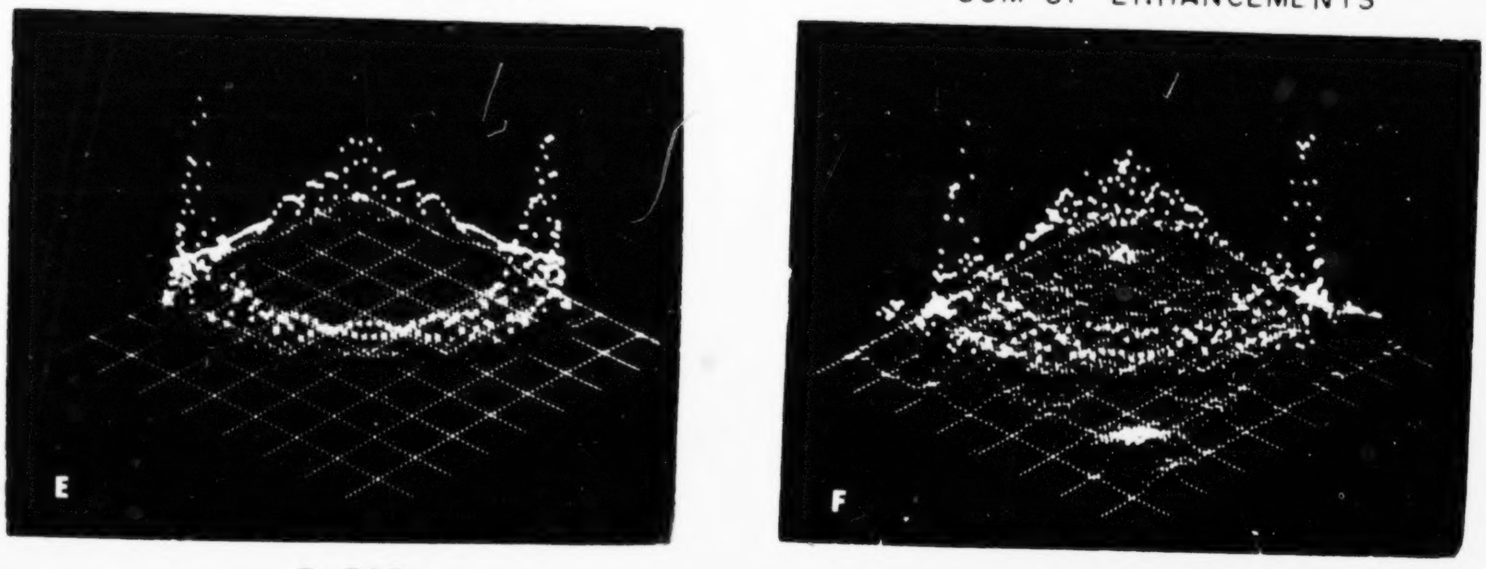
P-N SINGLET ENHANCEMENT

P-N TRIPLET ENHANCEMENT



P-P ENHANCEMENT

SUM OF ENHANCEMENTS



THEORY

EXPERIMENT

FIGURE 2. Theoretical simulation for D+P → P+P+N: the yield along the kinematic line is calculated according to a model, with independent terms presented separately in A, B, and C for normalization. The sum is shown in D and final theoretical values in E, for comparison with experimental results F.

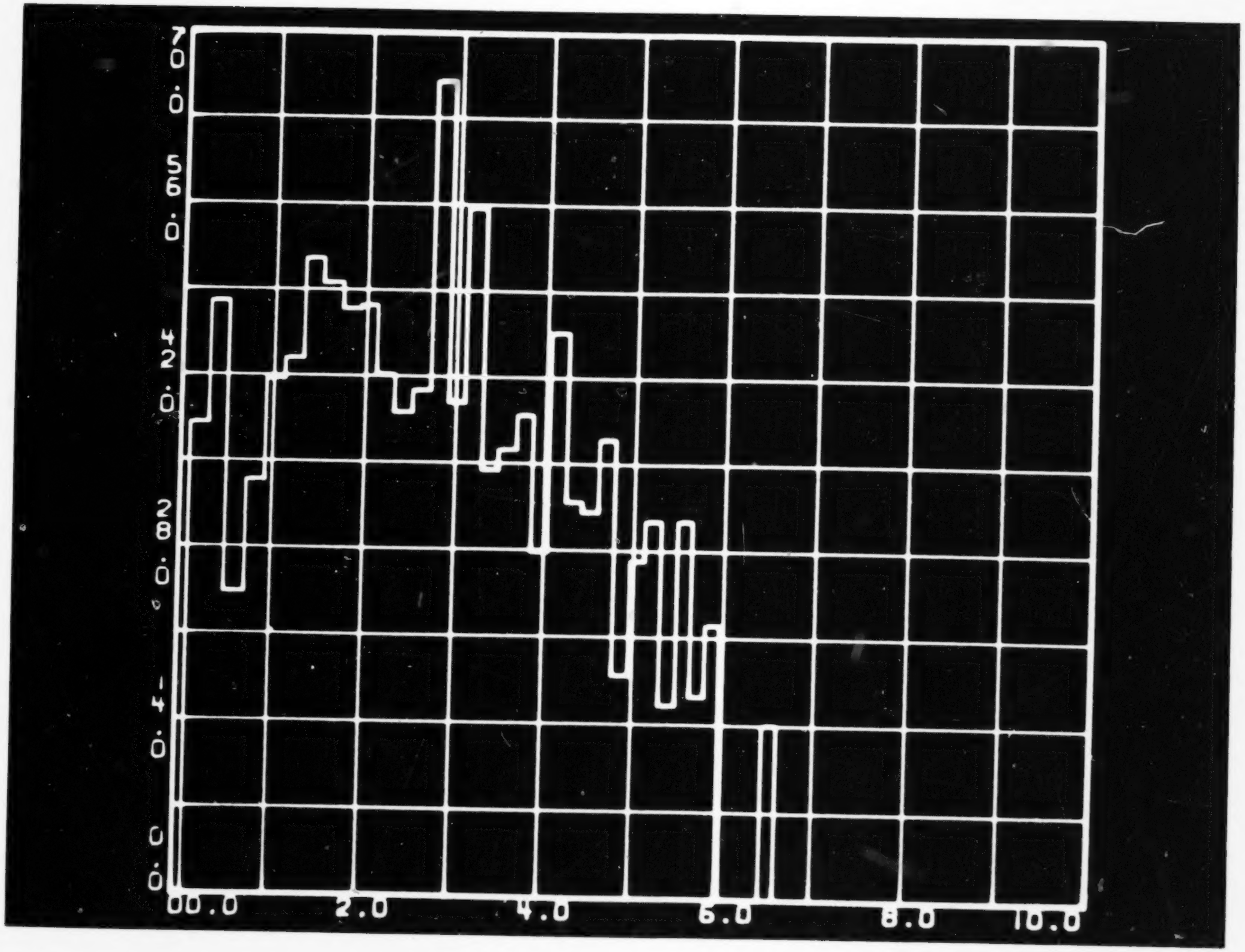


FIGURE 3. A more conventional presentation of results is seen in this histogram, drawn on the same CRT used in Figures 1 and 2. Here the number of events is shown as a function of excitation energy in an intermediate two-particle system, for the reaction ^{3}He+D → T+P+P.

a dot on the spectrum display, it sets the most significant bit in the data word. This bit is used by the display hardware to suppress further display of that dot; in this way the user is informed which dots have been tagged by the light pen, and the system is not clogged by events tagged more than once. After the light pen work is concluded, the program uses as input for analysis only those channels which have the leading bit set. In this way irregularly shaped kinematic lines may be separated from the surrounding background and the excellent pattern-recognition facilities of the human eye and brain interfaced to the computer in a convenient way.

The light pen is also useful in delineating a peak in one-dimensional spectra such as in Fig. 4. Here the background has been indicated by tagging the channels on either side of the peak. A quadriatic is then fit to the tagged channels and the resulting fit displayed. An erroneous fit may result from tagging channels too far up the shoulder of the peak, but this is easily seen and corrected. The facility for displaying the quality of the fit was quite illuminating when first employed; one wonders how often this happens on computers that lack display facilities.

Another interactive application of the display is shown in Fig. 5. Here the widths and strengths of five resonances

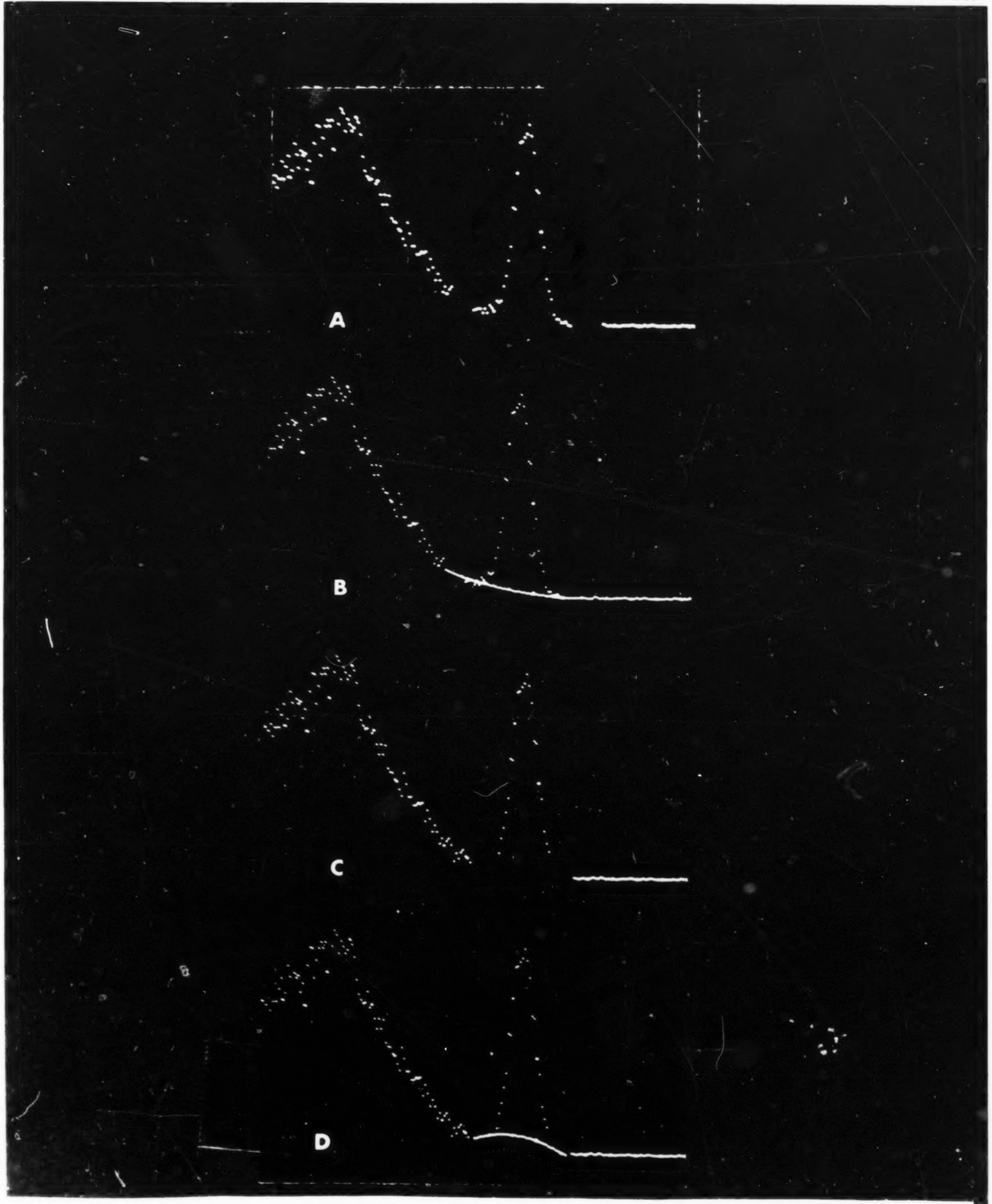


FIGURE 4. The light pen is used to select a peak for analysis, fitting the background to the selected (erased) channels on either side (A and B). If channels far up the peak are used (C), the quadratic fit is obviously wrong (D) and the process may be restarted.

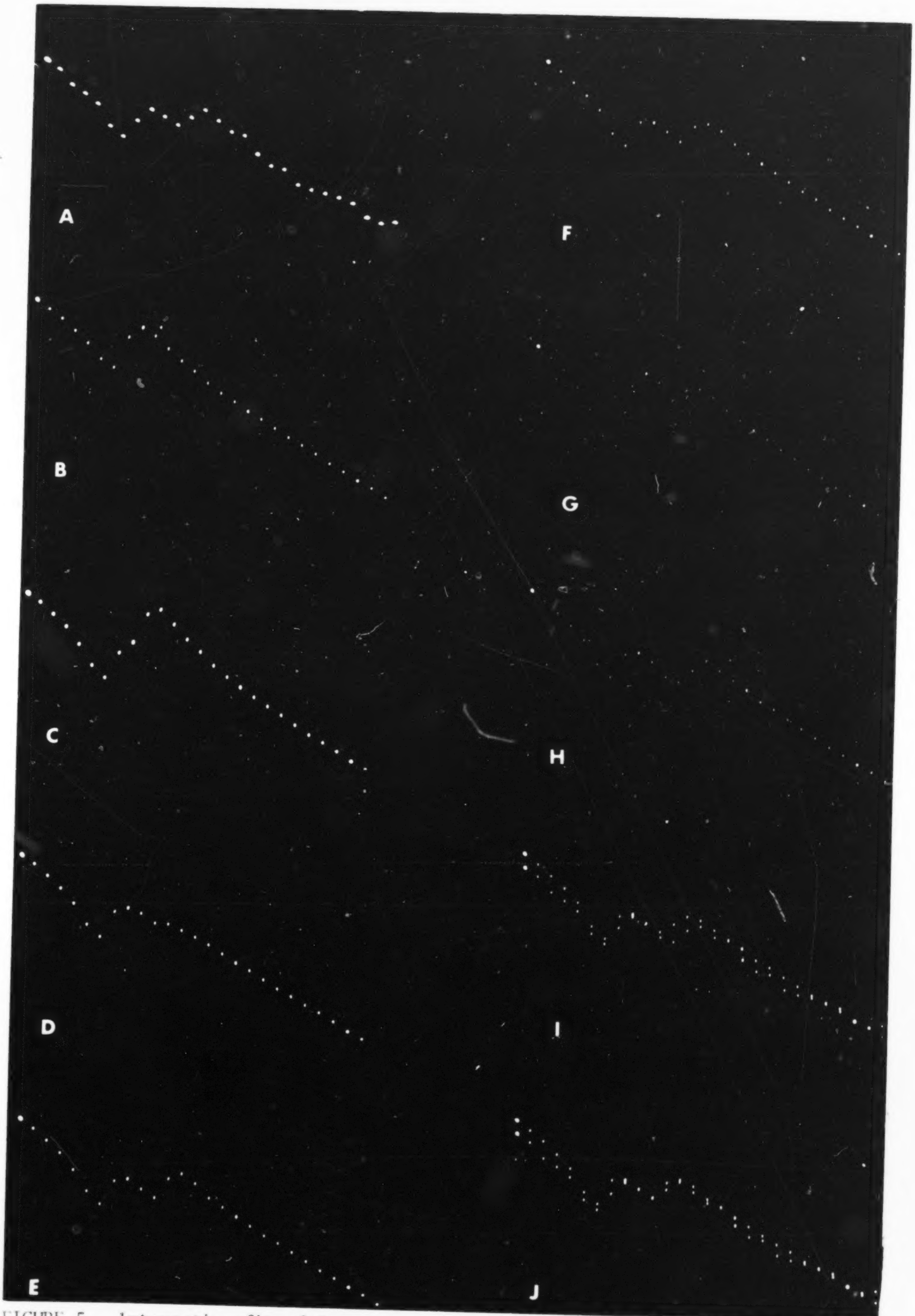


FIGURE 5. Interactive fit of 5 resonances to data (A) from inelastic scattering of protons on Pt^{194}. The positions of the resonances are known, but the widths and strengths are determined by inspection in B through H. Curves I and J compare the data with the calculations of F and H; J was selected as the best fit.

at known energies were fit to the data. By successive variation of the various parameters, a good fit was obtained in more computer time than the computer center would have required, but much less of the experimenters' time.[3]

System Growth

As noted before, there are myriad opportunities for a computer system to grow, even if the initial investment were small. Our original computer was a 910 with 4K of 24-bit words; this ran Fortran, but only relatively small programs, and the core size was increased to 8K within the first year. A second magnetic tape transport was installed to permit the running of a tape-based monitor, with a small card reader to aid program development and an incremental plotter.

Eventually the computer was in use 7 days a week for data collection, leaving no time for analysis or program development. Consequently the second computer, the 925, was installed, with a line printer switchable between it and the 910. The plotter was also placed on the switch as was a new and more reliable card reader.

This dual system has made it possible to run one experiment and one data analysis or other computation job at any one time. We have felt the need, however, for more data collection facilities and greater computation and analysis capabilities. A system is now under construction to meet these needs, as shown in Fig. 6. This system is far from small and far from simple. It uses a 32K 32-bit Sigma 5 as its main computer, with a satellite Sigma 2 for data collection. With only 4 users plus background, it will be possible to use a simple time-sharing

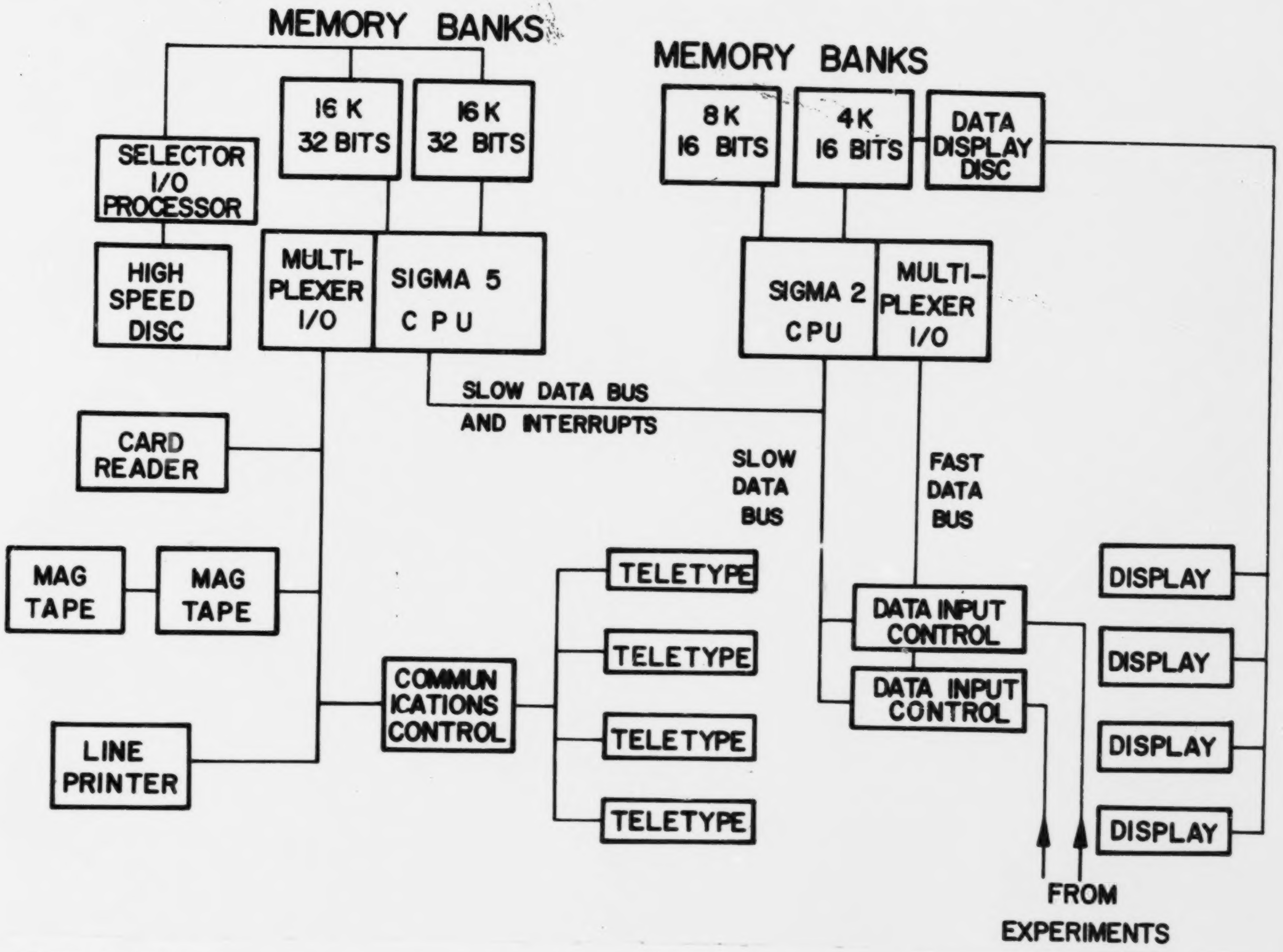

MEMORY BANKS
16 K 32 BITS
16 K 32 BITS
SELECTOR I/O PROCESSOR
HIGH SPEED DISC
MULTI-PLEXER I/O
SIGMA 5 C P U
MEMORY BANKS
8 K 16 BITS
4 K 16 BITS
DATA DISPLAY DISC
SIGMA 2 CPU
MULTI-PLEXER I/O
SLOW DATA BUS AND INTERRUPTS
CARD READER
SLOW DATA BUS
FAST DATA BUS
MAG TAPE
MAG TAPE
TELETYPE
TELETYPE
TELETYPE
TELETYPE
COMMUNICATIONS CONTROL
LINE PRINTER
DATA INPUT CONTROL
DATA INPUT CONTROL
DISPLAY
DISPLAY
DISPLAY
DISPLAY
FROM EXPERIMENTS

FIGURE 6. New computer system now in construction at the Rutgers-Bell nuclear physics laboratory. The data-acquisition computer (Sigma 2) will run under the control of the main computer (Sigma 5). The Sigma 5 will serve several users on a time-shared basis.

system to make the full facilities of the system available to all users.[4]

Two-Computer Operation on a Small Scale

The use of two computers in both our original and new systems provides full time data collection together with the supporting services of data analysis and program development. For small systems, there is no necessity that both computers belong to the accelerator laboratory. The computer center can serve as the second computer, if a means exists to get its output into the local computer. The best arrangement is a direct tie-in to a time-shared computer, but this facility is not generally available yet. So long as the ease of connecting peripheral computers is not a major hardware selection criterion for computer centers, the direct tie-in even to a non-time-shared computer will be difficult. Eventually, however, such connections will be routine.

At the very least, the computer center can at present provide support in the form of an assembler for the small computer. Program development at Teletype speeds is agonizingly slow, but a computer center can provide program listings and binary paper tape if the proper software is written for it. The turn-about time at the computer center may exceed the Teletype listing time, but the local computer can be collecting data in the meanwhile.

Slow I/O is a nuisance in the output of data from the computer as well as in program development, and here a direct line to the computer center can be effective also. Another interesting possibility, as yet little exploited, is the use of the ink-spray Teletype Inktronic printer. This device is an order of magnitude faster than the mechanical Teletype and costs much less than a line printer.

Interaction With the Experimenter

While some effective means of communication with a second computer is very important, communication with the experimenter is much more so. Properly handled, it can extend the experimenter's capabilities both in manipulating numbers or apparatus and also in achieving physical insight. The ability of the computer to explore models, to calculate quantities of physical interest, and to display them on a fast basis has enhanced our insight in many applications. The most important tools for this interaction at our laboratory have been the display and the light pen. With gain controls and sine-cosine potentiometers we are able to tip and rotate displays of two-paramenter data as if they were three-dimensional objects, making the complexity manageable.

Facilities of this sort are not expensive, since they require no precision mechanical components. Additional capabilities conferred by the light pen and CRT are text displays and on-line output of such information as the contents of scalers. Text editing is particularly important if larger computer card input is unavailable for program development, and is much more easily done with a display than by teletype alone.

By now computers have provided the benefits of interactive data handling to a majority of medium-size and large accelerators. At the current level of computer costs there is no barrier to their installation at any research accelerator.

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THE NEW YORK METROPOLITAN SECTION OF THE AMERICAN NUCLEAR SOCIETY, NEW YORK, N.Y. (proceedings of a symposium sponsored by): Applications of small accelerators. Saul J. Harris, Chairman.
U.S. Department of Health, Education, and Welfare, Public Health Service Publication Number BRH/CFS 70-2 (May 1970) 291 pp.

ABSTRACT: The Symposium was intended to provide present and prospective users of small accelerators with a concise review of current and future applications of such machines.

Small accelerators are considered to be those generally with operating potentials of up to 500,000 volts,

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Accession No.

THE NEW YORK METROPOLITAN SECTION OF THE AMERICAN NUCLEAR SOCIETY, NEW YORK, N.Y. (proceedings of a symposium sponsored by): Applications of small accelerators. Saul J. Harris, Chairman.
U.S. Department of Health, Education, and Welfare, Public Health Service Publication Number BRH/CFS 70-2 (May 1970) 291 pp.

ABSTRACT: The Symposium was intended to provide present and prospective users of small accelerators with a concise review of current and future applications of such machines.

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KEYWORDS: Accelerators; Computers; Contamination; Cyclotron; Ion Implantation; Machine Problems; Measurement; Medical Application; Neutron Physics; Radiation Protection; Shielding; Tritium Pump.

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